MENG

Optimising Bioenergy Use in District Heating Systems in the EU

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OPTIMSING BIOENERGY USE IN DISTRICT HEATING SYSTEMS IN THE EU

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"I certify that I have read and understood the entry in the Student Handbook for the Department of Mechanical Engineering on Cheating and Plagiarism and that all material in this assignment is my own work, except where I have indicated with appropriate references."

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ABSTRACT

Bioenergy, energy derived from organic material originating from plants, microbial cells and the waste and residues associated with their processing, accounts for the largest renewable share of final energy consumption (FEC) in the European Union (EU). Its contribution is only likely to increase as global movements to tackle the current climate emergency continue. The issue of climate change is not only addressed in global treaties, such as the 1977 Kyoto Protocol and the 2015 Paris Agreement but is also gaining traction with a new generation as young people across the world strike to bring attention to the need for action.

This report focuses on biomass powered district heating systems and optimising their use within the EU. Existing literature is examined to see how bioenergy systems have been analysed and highlights the importance of regarding both feedstock type and conversion technology in parallel for a thorough optimisation. Various optimisation methods are explored and a mathematical multi-criteria optimisation (MCO) is performed considering both environmental and economic performance. Two equations are investigated to explore the sensitivity of output to the objective function and the potential of changing this to suit different stakeholders is discussed. The BioGrace II tool is used to calculate greenhouse gas (GHG) emissions and emission reduction potential for 310 scenarios, across four countries. These are then ranked based on their potential for emission reduction and by their performance in the MCO which aims to minimise the output value. All scenarios offer emission reductions when compared to fossil fuel counterparts with values ranging from 11% to over 100%. The optimal biomass pathway is identified as the anaerobic digestion (AD) of manure in Spain, Germany and Poland to produce biogas with values of 0.26, 0.62 and 0.72 respectively. In Finland the optimum solution is the use of forest residue chips for CHP systems when replacing peat or coal achieving an optimisation value of 6.4, however combustion scenarios in Spain (straw) and Poland (forest residues) perform better than this at 3.1 and 3.4 respectively. A major limitation of this analysis stems from the inclusion of emission credits in the BioGrace tool due to improved manure management. This results in negative net total equivalent emissions for these pathways and reduction percentages over 100% which were difficult to analyse. To overcome this constraints were imposed which meant many AD process outputted the same optimisation value despite differences in transportation output or alternative fuel which was considered in the discussion.

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NOMENCLATURE

AD	Anaerobic Digestion
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CH_4	Methane
DH	District Heating
DHC	District Heating and Cooling
EC	European Commission
EU	European Union
FEC	Final Energy Consumption
FRC	Forest Residue Chips
FRP	Forest Residue Pellets
GHG	Green House Gas
GWP	Global Warming Potential
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment
LP	Linear Programming
LUC	Land Use Change
MCO	Multi-Criteria Optimisation
MILP	Missed Integer Linear Programming
NGB	Natural Gas Boiler
NLP	Non-Linear Programming
N_2O	Nitrous Oxide
NREAP	National Renewable Energy Action Plan
PEST	Political, Economic, Social and Technological
RES	Renewable Energy Sources
SWC	Stemwood Chips
SWP	Stemwood Pellets
WCB	Wood Chip Boiler

1 INTRODUCTION

1.1 CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS

The destruction of our planet through climate changes resulting from human activity is a long-standing global scientific and socio-political issue which is causing growing concern among a new generation. In early April 2019 students from the UK joined in a day of action that saw demonstrations in major cities across the world, inspired by the school strikes started by 16 year old Swedish schoolgirl Greta Thunberg (1). The link between human behaviour and climate change is widely recognised and the International Panel on Climate Change (IPCC) state that substantial and sustained reductions of greenhouse gas (GHG) emissions are required to limit global warming (2). To do this behavioural changes are required at all levels of society, but there are challenges, not least the economic costs of such changes. The 1977 Kyoto Protocol committed to reduce GHG's and was ratified by 192 countries. Following this the 2015 Paris Agreement created the first legally-binding global climate agreement with the action plan to limit the global average temperature to well below 2°C above 1990 levels with a target of 1.5°C (3). The more recent IPCC Global Warming of 1.5°C report compares the implications between a 2°C and a 1.5°C increase and highlights the profound potential for difference in an attempt to convey the severity of risks associated with inaction (4).

1.2 BIOENERGY

Bioenergy refers to energy derived from organic material originating from plants, microbial cells and the waste and residues associated with their processing (5). Biomass is considered a low carbon energy source as its combustion emits carbon that is currently part of the biogenic cycle (6) and is the only clean energy source able to provide heat, electricity and transportation fuel (7). Heat is the largest energy end-use globally and accounts for around 50% of final energy consumption (FEC) (8) demonstrating the large potential to reduce emissions within the industry. The development of biomass systems is key to meeting current legislative targets such as a 27% renewable energy sources (RES) share of FEC in the European Union (EU) (9) and in helping to tackle the increasingly prominent issue of climate change.

1.2.1 Biomass Feedstock and Conversion Technologies

Conversion technology and feedstock selection will have an effect on the energy and GHG balances of the bioenergy system (10) and are vital considerations in the optimisation process. Types of biomass used for bioheat in the EU are shown in Figure 1. Solid biomass accounts for the largest portion with most of this being woody biomass, burned as pellets, chips or logs (11). Wood in chip form is typically cheaper and more locally obtainable however pellets require less space for storage and transportation. The pelletisation process results in a hydrophilic end product more suited for long term storage meaning the pellets can be kept throughout the year and used when production levels may be lower reducing the need to import feedstock (12).

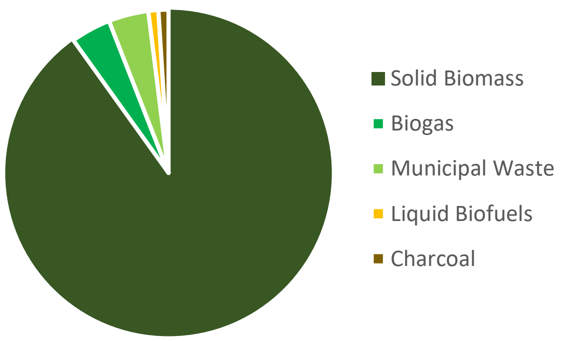


Figure 1- Types of biomass used for bioheat in the EU-28, 2015 (8)

Biomass feedstock can be converted into bioenergy via thermo-chemical and bio-chemical conversion processes. Figure 2 outlines the options available in each case (13). Combustion, gasification and digestion are well-established methods within EU member states that can be used to generate heat (14) (15).

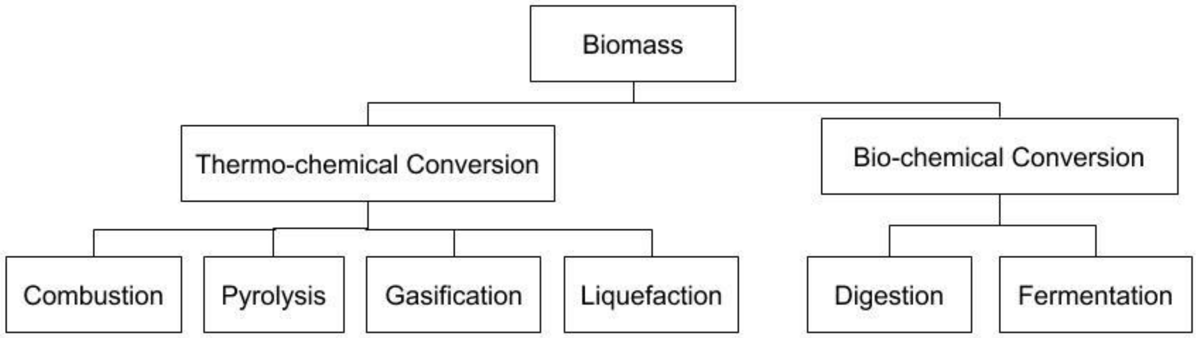


Figure 2 - Classification of biomass conversion technologies

1.2.2 EU Policy and Legislation

Two key pieces of European policy include the Renewable Energy Directive 2009 and the Biomass Action Plan 2005. The former creates binding national targets with the overall effect of reaching a 20% Renewable Energy Sources (RES) share of FEC by 2020. It addresses the need for improved legislation and sets about targets for biomass conversion efficiencies in member states: 85% for residential and commercial application and 70% for industrial application (16). The Biomass Action plan recognises that biomass is slowest growing within the heat energy vector and advises that legislation addressing this must be created to bring about change and recommends district heating (DH) technologies are included in reduced VAT rates. The plan suggests the development of biomass within DH is easier than individual heating (17). Both suggest a positive outlook within the EU for the use and development of biomass DH systems.

1.2.3 Environmental, Economic and Social Impact

An increased penetration of bioenergy will have wide ranging impacts on an environmental, economic and social level. Generally the environmental impact of bioenergy is considered to be positive due to the potential for reduction in GHG's. However, the use of chemicals in the cultivation process can have negative connotations with water and air quality (18). Environmental impact is often assessed by means of a life cycle assessment (LCA), which requires consistent system boundaries to be established. The boundaries for the bio-chain will include emissions associated with production, harvest, transportation, processing and use. Land use changes and disposal can also be considered. A representation of this system, alongside expected considerations, is given in Figure 3. Economic impact is a key concern in policymaking and often forms the primary stage of evaluation (18). Energy must be produced in a cost-effective manner and competing channels for the resource must be considered, for example the economic payoff between use of land for fuel or food. This is also a cornerstone in the environmental and social debate. Additional social considerations include the creation of jobs, opportunity for rural development and changes to food security. The changing cost of feedstock must also be considered as an increase in demand will creative competitive market conditions and has been linked to changes in food price (19). Environmental, economic and social considerations must all be considered to implement a sustainable solution.

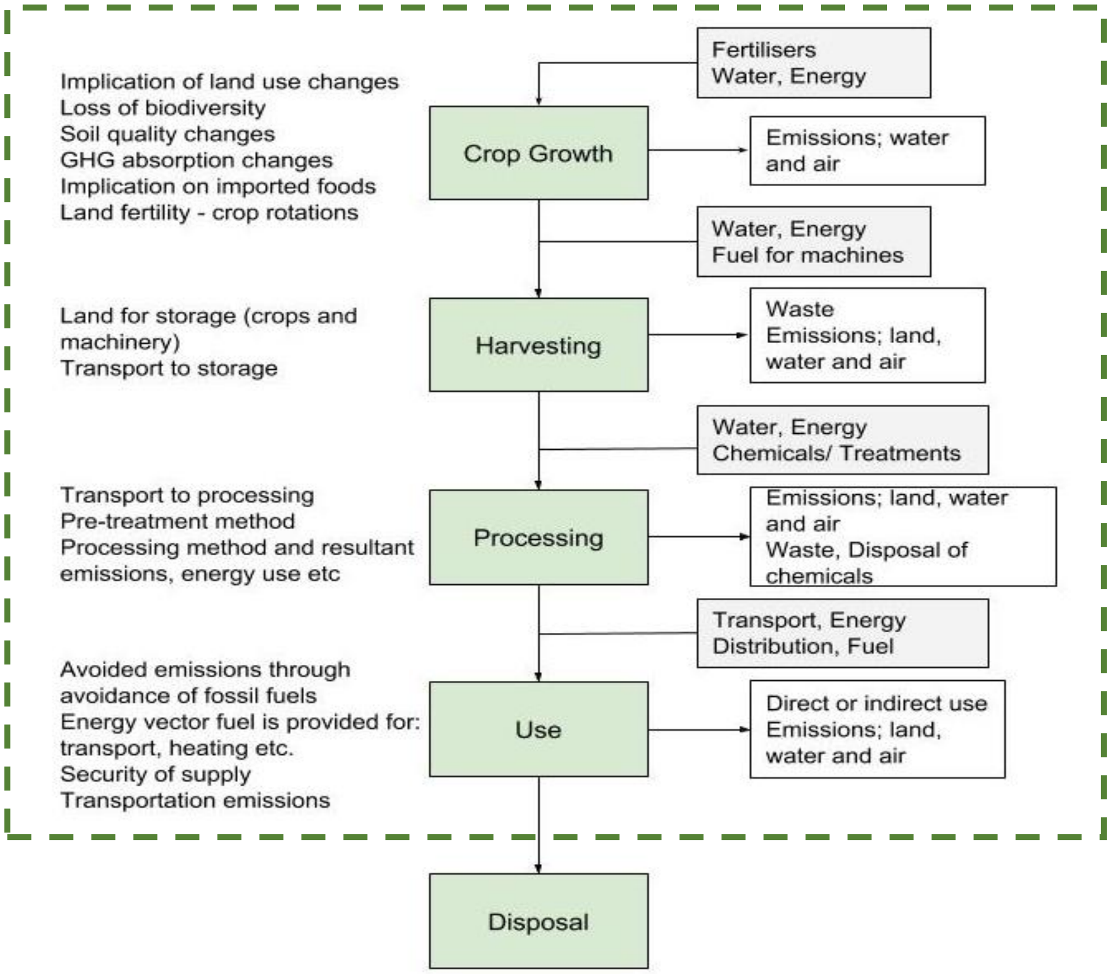


Figure 3 - LCA system boundaries for bioenergy pathway

1.3 District Energy Systems

District heating and cooling (DHC) networks offer an attractive technology, which has displayed significant opportunity to reduce carbon dioxide emissions and improve energy security (20) (21). They operate from a single point of generation and transport energy to the consumer through a network of insulated pipes (20). Current DHC accounts for 9% of the EU-28 heating market, with 40% of this fuelled by gas, 29% by coal and 16% through biomass (22). Within the EU the countries with over 30% share of bio heat consumption through district energy systems are Denmark, Lithuania and Sweden and will act as exemplar cases (7)(Appendix I). District heating can also be integrated with other renewable technologies and has been highlighted in the EU strategy on heating and cooling as an area for improvement and investment. DH is often looked at in combination with combined heat and power (CHP) plants (22).

1.4 AIMS AND OBJECTIVES

The overarching aim of this research is <u>to **determine the optimum use of bioenergy for district heating systems within the European Union**</u>**.** This will be achieved through the following objectives:

1. Outline the heating demand in the EU

Establish typical load profiles for member states and explore how this profile varies throughout the EU with particular interest in peak and baseload demand. Recognise the share and size of district heating demand for member states.

2. Outline the current heating supply

Research the current heating supply in EU countries to see how they are meeting current demand. Acknowledge any legislation that may be driving current decisions or will affect future targets. Research current successful district energy systems and create case studies on these exemplars.

3. Establish how bioenergy can meet the identified demand

Establish the bioenergy potential of countries with regard to feedstock and conversion technology. When considering different countries look at other driving factors such as geographical location, social and political factors and acknowledge how this could affect the solution.

4. Develop potential scenarios and pathways for comparison

a) Use the reviewed literature to create a list of potential scenarios.

b) Collect the data needed for each scenario: GHG emission data; energy balances; LCA's; and normalise where required.

c) Analysis to ensure data from different sources is comparable.

5. Perform optimisation

Perform a literature review on optimisation method and develop an appropriate method to optimise with primary regard to minimise environmental impact.

Run each scenario from objective 4 through the optimisation equation and analyse and discuss the results.

6. Demonstrate benefits of solution

Create a detailed and justified design solution to establish the optimum use of bioenergy in district energy systems in the EU. Evaluate the solution and the methodology used to achieve it. Consider how this optimised method can be applied in a wider sense such as to other energy vectors.

7. Consider the future work that can further develop this research

This work has been allocated to five work packages, which are outlined in more detail in the preliminary report to this research (23).

1.5 Outline of Report (Report Roadmap)

The report is structured to include a literature review highlighting key research within the field, critically analysing this and identifying a gap to justify the undertaken project. Optimisation techniques used in related studies will be analysed and appropriate analysis methods will be established. Existing cases of district heating within Europe will be used to create case studies detailing the practices used. A scoping stage will be conducted to assess how best to narrow the field of research in a manner that allows an EU wide optimisation to be investigated whilst meeting the 11 week project timeframe. A number of sources will be used to gather data on emissions, resources and costs; this will be used to create scenarios for optimisation and the results of these will be compared. In the discussion section key findings will be addressed and the report will conclude with a recommendation for the optimal use and expansion of biomass within the European Union. The structure is presented in Figure 4.

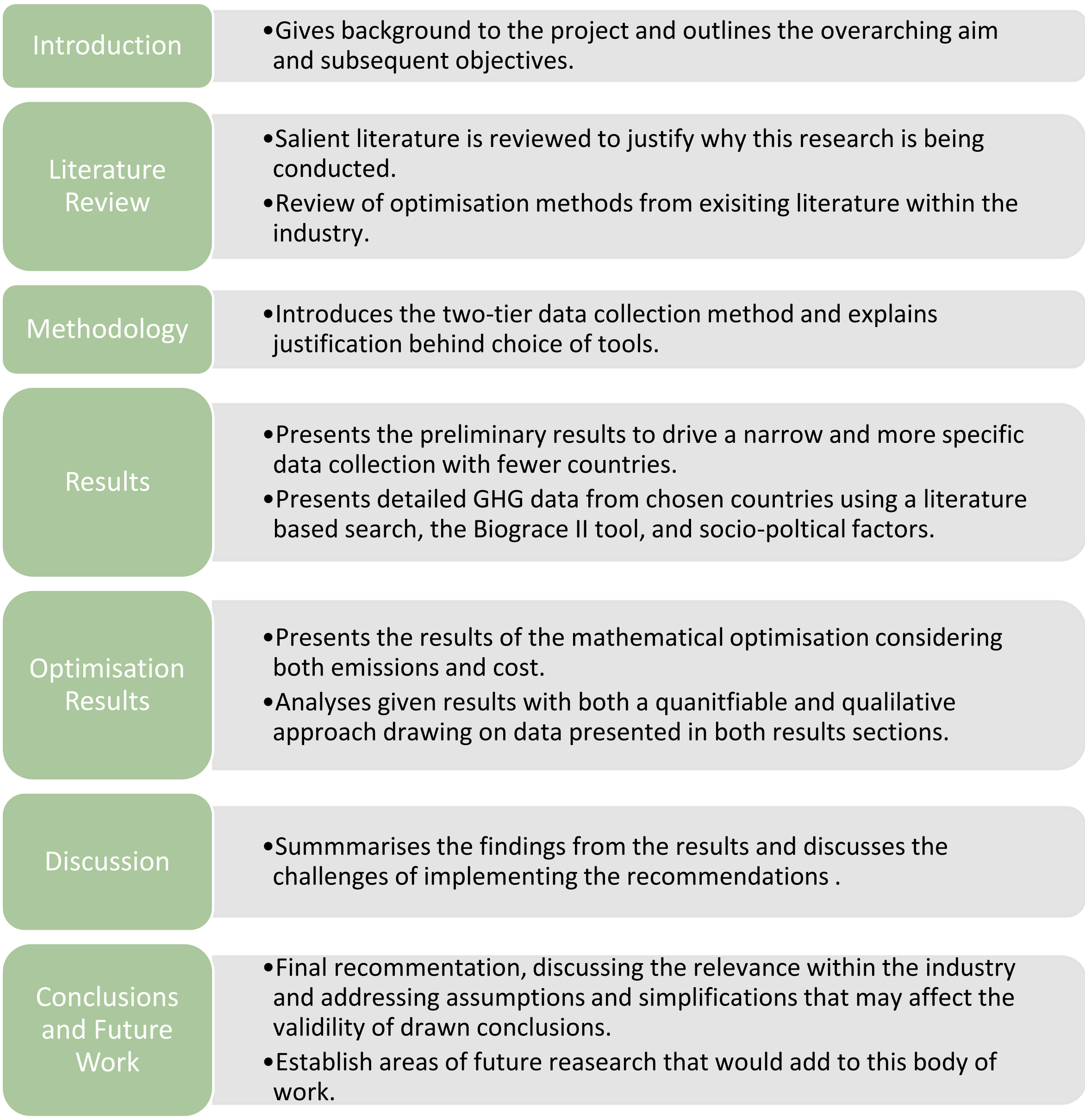


Figure 4 - Flowchart detailing report structure

2 LITERATURE REVIEW

2.1 EXISTING STUDY STRUCTURE

A number of studies looking into the optimal use of bioenergy have been reviewed to evaluate the methods used and to identify a gap in the current literature to provide justification for this research.

There is conflict of opinion regarding the benefits of optimising with respect to many or few scenarios, with Steubing et al. employing a method reviewing around 1500 combinations of feedstock and conversion route across all energy vectors (24). El Akkari et al. published an analysis of the GHG reduction of bioenergy using a similar method to Steubing et al. Multiple feedstock options were considered and land use change (LUC) was regarded to create an optimisation with many scenarios. El Akkari et al. concluded that second generation biofuels and bioelectricity as a substitution for fossil fuels provide the optimum GHG reduction potential (25). Conversely Scott et al conclude that optimisation methods choosing from few alternatives are more popular compared to those regarding a large number of alternatives (26). This presents an interesting conflict of opinion. The impact of many factors in bioenergy would suggest that more scenarios are preferable as this enables the user to consider the system from many angles and to appreciate interdependencies. However, the conclusion that fewer alternatives are more popular is not a surprise and may reflect the difficulties encountered when comparing and contrasting data from different sources. Time constraints and associated costs will be a consideration that is likely to drive the researcher to narrow the field of scenarios.

The level of analysis can be seen to vary across studies with each taking a different approach to the feedstock or conversion technology considered. Steubing et al consider the combustion of residual and waste biomass and concludes that woody biomass is most beneficial when substituted for coal (24). However this conclusion is limited as additional pathways, such as anaerobic digestion (AD), have been neglected. A review into district energy systems in Sweden conducted by Difs et al to establish the opportunities surrounding biomass gasification uses a similar approach with a limited consideration of conversion technology. The report identifies the need for further analysis into other technologies and fuel mixes, demonstrating the complex nature of considerations with biomass use. Akkari et al consider only feedstock selection and neglect alternative conversion technologies. Both feedstock selection and conversion will have an impact on GHG emissions and should be reviewed in parallel for a thorough optimisation (23). The European Commission (EC) report uses a higher-level analytical approach to consider the optimal use of bioenergy in the EU. The report looks at biomass use across different energy vectors and provides a broader appreciation of the challenges, but does not optimise for a specific solution. It considers GHG savings, LUC, employment and costs to evaluate five higher-level policy options. The difference in outcome demonstrates the variation of solution when optimising with regard to different factors (27). It is clear there is merit to all levels of analysis, however to seek a specific quantifiable outcome a more detailed approach, such as that seen in academic literature, may be appropriate. The higher-level view is often useful as a decision aiding tool and for guiding policy which warrants its use by the EC.

2.1.1 Justification for Research

This research aims to add to the existing body of literature by providing a focused study on biomass use within district heating systems. Addressing the wide range of potential considerations and scenarios would not be possible in the project timeframe. Performing a focused study on one method of biomass based heating can ensure that appropriate feedstock and conversion technologies are considered, thereby addressing some of the limitations discussed in the reviewed literature. Thus far, optimisation has been performed on wider systems, for example to determine the optimum energy vector, or at a more detailed level considering a particular conversion technology. This research aims to bridge this gap by providing a more wide ranging optimisation, with multiple feedstock and conversion technology combinations, and applying this specifically to DH systems (23).

2.2 Optimisation Methods

De Meyer et al set out the main methods of optimisation as mathematical programming, heuristic approaches and multi-criteria decision analysis. Mathematical programming approaches often work to maximise or minimise an objective function and can include linear programming (LP), missed integer linear programming (MILP) and non-linear programming (NLP). Mathematical models are the most common method employed to optimise economic objectives, with MILP the most frequently applied (28). Heuristic approaches aim to reduce runtime and will seek a satisfactory solution to achieve this and therefore this method is unlikely to be suited to optimising bioenergy use to reduce GHG emissions. Multi-criteria optimisation (MCO) methods are well suited to the multi-faceted nature of bioenergy and allow considerations at varying decision levels. They have been identified by Čuček et al and Ortiga et al as useful tools within the field (29) (30). To further establish the most appropriate method additional research utilising varied optimisation approaches have been critically analysed.

Wetterlund et al look at the optimum use of forest residues for use in biofuel and CHP production. A simple MCO mathematical method is employed to consider both environmental and economic factors. The model works to minimise total costs through the implementation of the equation;

$$\textit{total cost} = \textit{cost supply chain} + (\textit{emissions supply chain} \times \textit{cost for emitting } CO_2) \text{ (31).}$$

This method would work well for the proposed research, as system boundaries can be set through clear definitions of supply chain costs and emissions. The data required is obtainable and the optimisation can be performed with readily available software. Durusut et al discuss the use of the BioHEAT model, a techno-economic model that aims to incorporate multiple criteria including consumer behaviour, policy interventions and interdependencies between end use sectors (32). The model is highly complex and goes beyond what is needed for the scope of this research but demonstrates the highly complex nature of biomass optimisation and the creation of specific tools to address this.

Lam et al work to minimise the carbon footprint of regional biomass supply chains using a LP mathematical method within a regional cluster algorithm to simplify the scope of the problem. Surplus-deficit curves are analysed at each cluster alongside regional resource management composite curves to show energy imbalance within the region. Pay back analysis is then conducted to introduce an economic perspective and can be used as a trade-off with the carbon footprint reduction (33). This method works well when optimising within a smaller scope as the regional analysis can be conducted between district energy systems within a country. To analyse the situation for the EU, as required in this project, would require large generalisations to group countries into clusters, and therefore may prove unsuitable.

The final reviewed study by Daub et al. looks to use a LP model to optimise the course of heat supply for a small village. Three basic components are identified: the model's variables; objective function; and constraints. By definition a linear model is characterised by the absence of squaring, cubing or multiplying the variables by one another in the objective function or constraints (34). An objective function was created to maximise the net present value of the heat network. The method is employable on readily available software and highlights the importance of creating a relevant objective function that will effectively optimise with regard to the factor of importance, which for this research will be GHG emissions.

3 METHODOLOGY

3.1 SCOPING DATA

Initially district heating was analysed at an EU level to give an indication of the available resources and current penetration of DH systems. To give background knowledge case studies were performed on countries that are currently using the technology successfully (Appendix I). A database was created detailing share of renewable energy sources (RES), current district heating demand and supply considering current fuel mix and current production, import and export levels for potential feedstock sources. This was done for all EU member states using Eurostat as a consistent and reliable source for all data. A higher-level analysis of the data allowed 4 countries of focus to be selected based on the greatest potential for impact, with emphasis on countries that currently use the largest gross amounts of solid fossil fuel and gas. Demand profiles were used to highlight the countries with higher summer demand to account for a variation in climate within the sample countries. To complete objective three, biomass potential was analysed using the Atlas of EU biomass potentials from the European Commission. This gave predicted biomass potential and cost for a 2020 reference scenario. A political, social, economic and technological (PEST) analysis was conducted to determine external factors that will influence results. Although a detailed optimisation of these factors lies outside the scope of this research, current policy was identified and a qualitative higher-level analysis identifies barriers to uptake and level of risk. This can be considered alongside the optimisation results to draw more rounded conclusions and highlights the multi-disciplinary nature of the work that could be further investigated at a later date.

3.2 EMISSIONS DATA

This research will focus on optimising bioenergy use for maximum environmental benefit. GHG's will be classified as in the Kyoto agreement and the analysis will focus on carbon dioxide, methane and nitrous oxide (35).

3.2.1 Literature Based Methods

A two-tier system was implemented to collect and corroborate data. Initially the university library database was used to identify journals containing GHG emission data for various bioenergy feedstocks. Key words and phrases were used to narrow search results and obtain journals quoting figures for emissions associated with bioenergy from cultivation through to use. In addition datasets were explored with particular emphasis on the Ofgem Biomass Sustainability Dataset. Maximum and minimum emission values were recorded for each feedstock type. This wider level research provided a window of acceptable range within which the final values will be expected to fall. It also gives an appreciation of the sensitivity of results to the system boundaries used and highlights the importance of maintaining a consistent data source to minimise against the adverse effect of this during data analysis.

3.2.2 Calculation Tool Methods

The initial research highlighted the potential risks of using multiple data sources and it was therefore decided to use a predesigned calculation tool as the single data source. A number of potential tools were considered including GEMIS, BEAT2 and BioGrace. The advantages and disadvantages of each have been highlighted in Table 1 and informed the decision to move forward using the BioGrace version two GHG calculation tool for electricity, heating and cooling as it presented the best compromise between accuracy and suitability within the timeframe.

Table 1 - Comparison of available biomass GHG calculation tools

TOOL	ADVANTAGES	DISADVANTAGES
GEMIS	Database of cost and environmental data for life cycle systems Analyse for different system boundaries and give GHG breakdowns Evaluate for multiple objectives – optimise for certain features	Not user friendly Complex nature requires multiple inputs that are difficult and time consuming to source
BEAT2	Presents and evaluates complex life cycle data User friendly Varied feedstock and technology Includes emissions and costs breakdown	Cannot ensure data is always accurate and may not meet individual requirements Limited flexibility in modelling outside of UK
BioGrace II	Presents breakdown of GHG data at each point; cultivation, transport etc. User friendly Easy to edit inputs to model different countries, alternative fuels etc.	Assumptions have been made in data collection process Manure management GHG credit applied
Journals	All feedstock and technology options Country specific data can be found Can assess validity of data; ensure peer reviewed, good methodology etc.	Difficulty comparing data from different sources Time consuming to source data System boundaries differ

Using the scoping data a number of scenarios were modelled to reflect the feedstock potential for the 2020 reference scenario and the fuel type that this could replace. Inputs to the BioGrace tool were changed to represent country specific factors including gross efficiencies and fossil fuel emission factors. Literature searches were used to determine these values and where country specific information was not available, EU average values and IPCC guidelines have been used for efficiencies and emission factors respectively. The final values with relevant sources can be found in Table 2 and Table 3. When considering anaerobic digestion (AD) the model assumed closed storage of digestate and distances considered ranged from 5-500km with the manure transported by truck. For the production of biogas with CHP, the surplus heat was set to be 'used usefully' at a share of 40%, representing the maximum efficiency in best practice (36), shown in Figure 5. Additional inputs, such as moisture content and transportation fuel types, were taken as default model values. The model was run for a total of 310 scenarios varying country, feedstock type, conversion technology, output type, alternative fuel or distance in each case. The transportation lengths for combustion technologies were initially set in the default blocks; (0-499km, 500-2499km, 2500-10,000km and over 10,000km), with the opportunity to change this at a later date in more detailed analysis. Analysis of energy potential referred to stemwood whilst the BioGrace tool offered analysis for roundwood and the names were used synonymously. This was considered to be an effective assumption based on the definitions given in existing literature where the terms have been regarded with minimal difference (37). Total emissions in grams CO_2eq were recorded, alongside the breakdown of these in grams of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The tool calculated total emissions using default global warming potential (GWP) values to reflect the ability of each GHG to trap heat in the atmosphere. The reduction in emissions was calculated using the emission factor of the alternative fossil fuel. However, this created issues when manure emissions were considered in credit, due to improved manure management, as a net negative emission value resulted in percentages above 100%

that were difficult to compare as reduction percentages. This has been addressed in the optimisation process.

Table 2 - Emission factors for fossil fuels (38) (39)

	Emission Factor (gCO_2eq/MJ)			
	Peat	**Coal**	**Oil**	**Natural Gas**
Finland	105.9	94.6	-	55.3
Germany	-	86.7	74.5	56.0
Poland	-	95.2	72.3	55.0
Spain	-	99.8	73.6	56.6

Table 3 - Typical biomass boiler and AD efficiencies (40) (41)

	Boiler Heat (%)	Boiler CHP		AD CHP*	
		Thermal (%)	**Electrical (%)**	**Thermal (%)**	**Electrical (%)**
Finland	87	67	19	49	36
Germany	85	71	19	49	49
Poland	84	65	20	49	49
Spain	74	71	16	49	49

**AD CHP efficiencies were assumed to be equivalent across all nations. In reality efficiency could be optimised for either heat or power and real values will vary.*

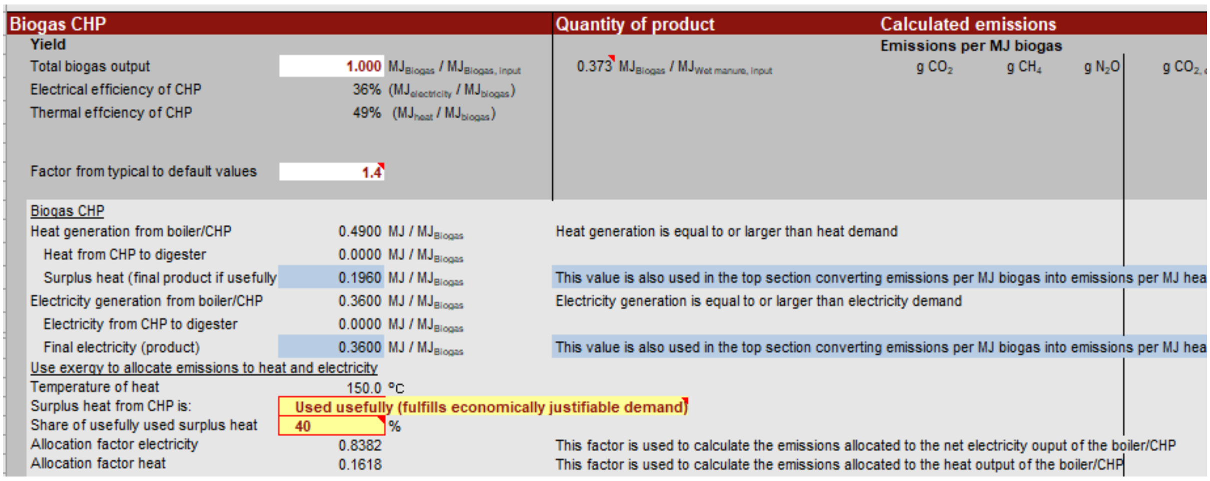


Figure 5 - Surplus heat inputs for biogas CHP

3.3 Optimisation

To perform the optimisation a multi-criteria mathematical programming approach was applied, incorporating an environmental and cost component. Two equations were created considering both linear (equation 1) and nonlinear (equation 2) methods and aiming to minimise the outcome of the objective function. When considering environmental impact both total emissions and the inverse of the emission reduction were included to represent actual and avoided impact respectively. Costs were considered in both equations, however in equation 2 potential is also included. This introduces a slight bias against those with greater biomass capacity however, when this is removed the cost component is negated and the optimisation returns results equal to those obtained by sorting from greatest emission reduction to smallest. In addition, the database can be filtered by a single factor such as emission reduction or feedstock cost for single criteria analysis.

$$f = \left((1 - E_R) + E_{EQ}\right) + \frac{Cost}{10} \qquad [1]$$

Environmental *Economic*

$$f = \left(\frac{1}{E_R} \times E_{EQ}\right) + \frac{Cost \times Potential}{10^6} \qquad [2]$$

Where: E_R *= Reduction in emissions (%)*
E_{EQ} *= Total GHG emissions (g*CO_2*eq)*

When optimised, AD processes proved problematic due to the negative equivalent emission value and percentages that did not accurately reflect the benefits of subtitling for each fossil fuel. To counteract this, constraints were incorporated into the optimisation process with a maximum reduction percentage of 100% and minimum equivalent emissions of 1g CO_2eq. A proportionality method was considered, taking the coal reduction percentage as the final value and minimising the natural gas value so that the ratio reflected actual emissions. However, this was deemed unacceptable, as percentages would no longer be comparable with combustion data sets. It must be noted that by using constraints the optimisation does not account for transportation distance and almost all AD scenarios for a specific country will return the same optimised value ranking them equally.

3.4 Data Availability

Difficulties were encountered when attempting to locate DH data for Spain. Currently there is limited DH penetration in the country; however cooling demand is relatively high and growing due to the mild winters and hot summers (42). The Spanish statistical body does not keep record of the DH fuel mix meaning this data is missing from the Eurostat database. Often simplifying assumptions have been made to model Spanish trends and behaviour, which introduce inaccuracies and a lack of consistency in the method. The use of a specific tool to gather GHG emission data, BioGrace II, limited feedstock selection and it is apparent this tool is more suited to wood based and waste analysis, making it difficult to analyse a large portion of Spanish bio potential (grassy perennials and prunings). It was decided that moving forward primary emphasis would be on those countries with accessible data, and where possible analysis would be extended to Spain. This has highlighted the benefit of analysing like-for-like countries, as those with a warm, dry climate more suited to grassy perennials and prunings require a tool with wider feedstock selection and more sophisticated monitoring of DH fuel mixes from national energy bodies.

4 RESULTS

4.1 HIGHER LEVEL ANALYSIS

Higher-level analysis was used to narrow the scope of the research and focus on four countries, with key results highlighted in Table 4. Finland, Germany and Poland were chosen as they displayed a sizeable DH demand that was being met with the greatest gross fossil fuel usage. This creates a large potential for positive environmental impact if alternative, clean energy sources can be used in an optimal manner. To apply the research on an EU level, countries with high cooling degree days[1] were considered. Spain was selected to reflect this climate as it was least affected by the lack of DH data.

Table 4 - Initial country rankings in higher level analysis (43) (44)

Factor	First	Second	Third
Largest DH Demand	Germany	Poland	France
Lowest RES share of DH	Poland	Czech Republic	Netherlands
Largest Coal use in DH	Poland	Germany	Finland
Largest Oil use in DH	Finland	Netherlands	Germany
Largest Gas use in DH	Germany	France	Czech Republic
Highest Heating Degree Days	Finland	Sweden	Estonia
Highest Cooling Degree Days	Cyprus	Malta	Greece

A contextual background has been provided for each country of focus using IEA country profile data (45)

FINLAND

- World leader in second-generation biofuel due to abundant forest resources. National targets focusing on transportation sector.
- Cold winters and relatively mild summers.
- Population: 5.5 million
- GDP: 252.7 billion 2010 USD

GERMANY

- Phased out coal and set out Energiewende (Energy transition) which targets a 50% RES share of all electricity
- Warm summers and mild cloudy or cold winters. Colder in Alpine regions.
- Population: 82.4 million people
- GDP: 3781.7 billion 2010 USD

POLAND

- Coal dominates the power sector and provides substantial employment. Energy plan to decarbonise transportation sector.
- Temperate climate with warm summers and relatively cold winters.
- Population: 38.4 million
- GDP: 572.7 billion 2010 USD

SPAIN

- Previous focus on balancing electricity regulated costs and revenues. Large natural gas capacity and driving new focus on GHG emissions and managing demand.
- Mostly Mediterranean climate with hot summers and mild winters.
- Population: 46.5 million
- GDP: 1464.5 billion 2010 USD

[1] Cooling degree days index measures the severity of heat during a time period with consideration to outside temperature and average room temperature thereby giving an indication to the need for cooling.

4.1.1 Demand Profiles

Annual district heating demand was found for all member states of the EU, shown in Figure 6, and is largest in countries with cooler climates and large populations. Germany, Poland and Finland fall in the top 5 EU countries for gross DH consumption, presenting a high potential for positive environmental impact, and a pre-existing knowledge base to implement solutions into, thus minimising barriers to uptake.

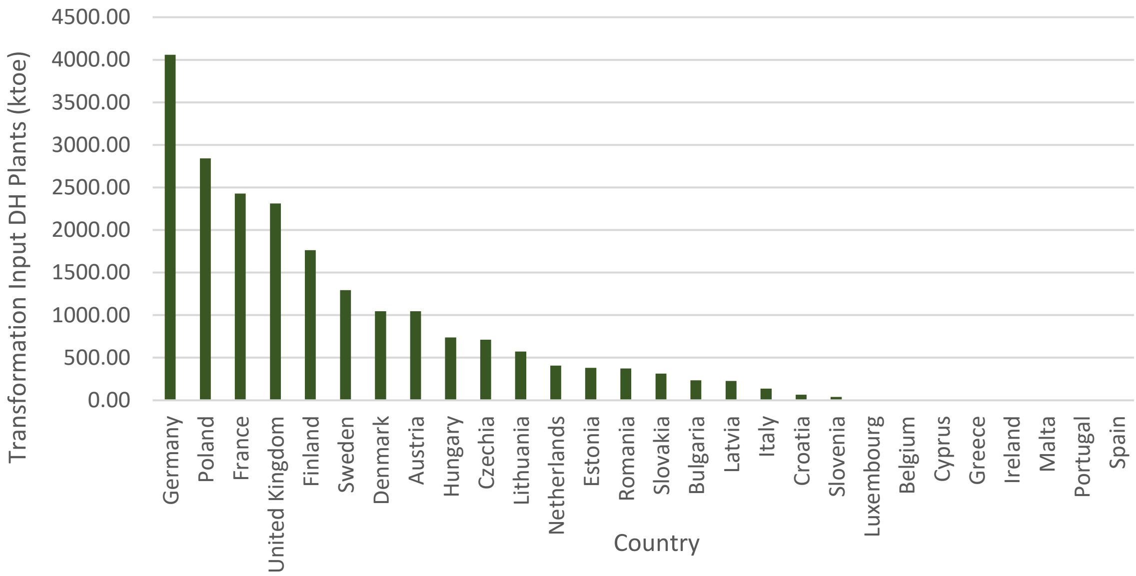


Figure 6 – Annual district heating demand for EU member states, 2016 (43)

Typical load profiles were found for the four chosen countries and are given in Figures 7-10. Key points of note include the higher demand on a winter's day for Finland, Poland and Germany. Spain displays the opposite trend signifying the market for cooling technologies may be greater.

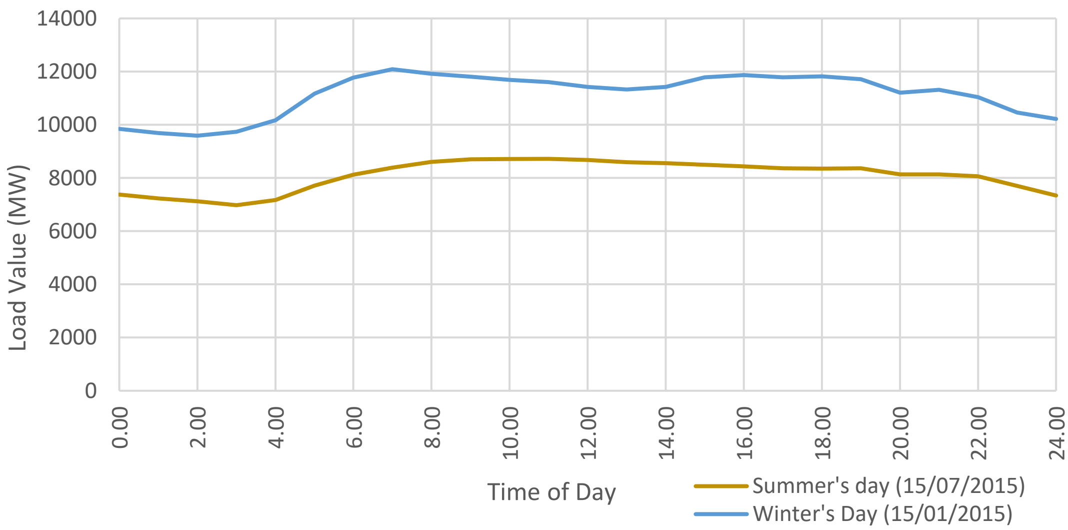


Figure 7 - Typical load profile for summer and winter day in Finland (46)

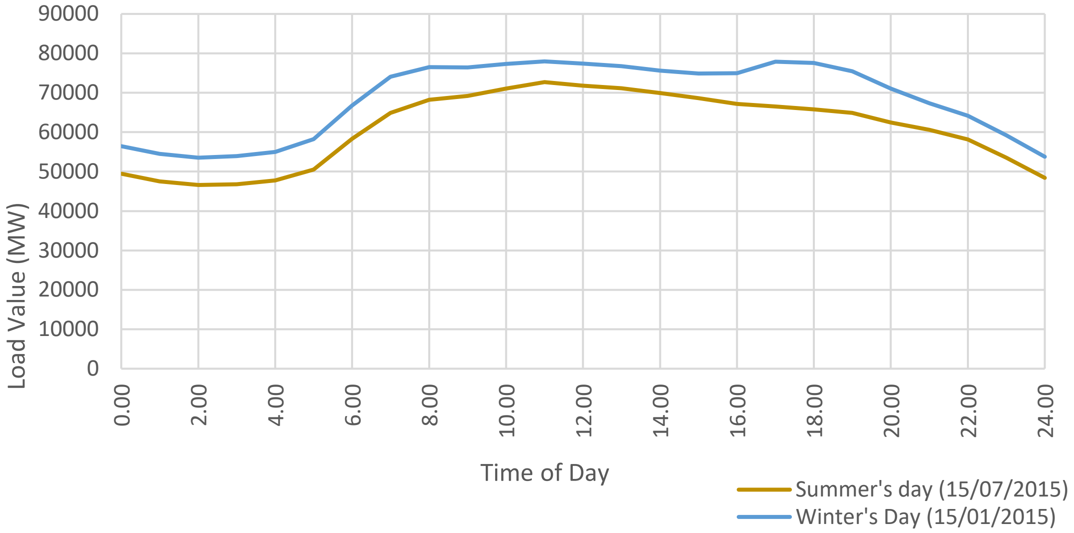


Figure 8 - Typical load profile for summer and winter day in Germany (46)

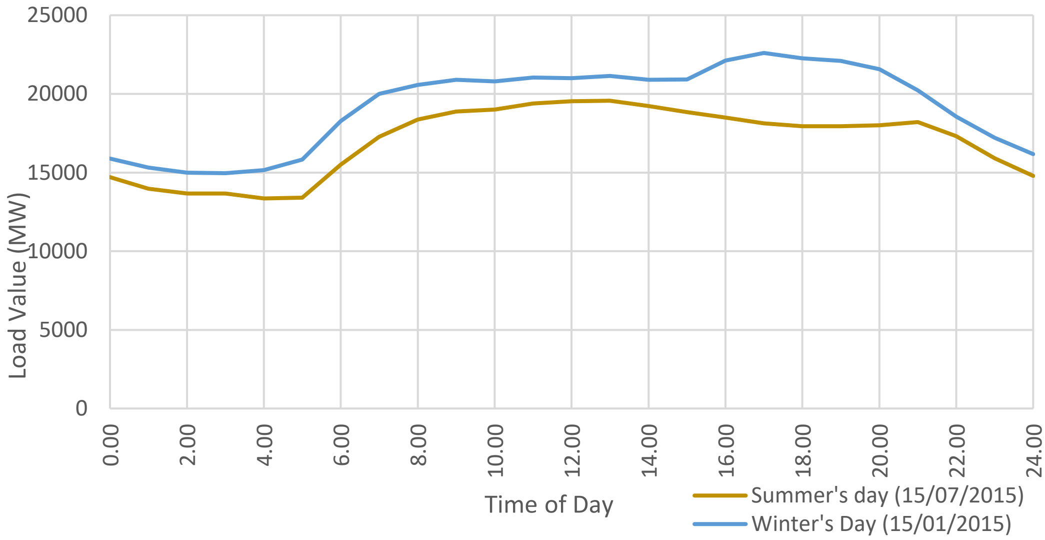


Figure 9 - Typical load profile for summer and winter day in Poland (46)

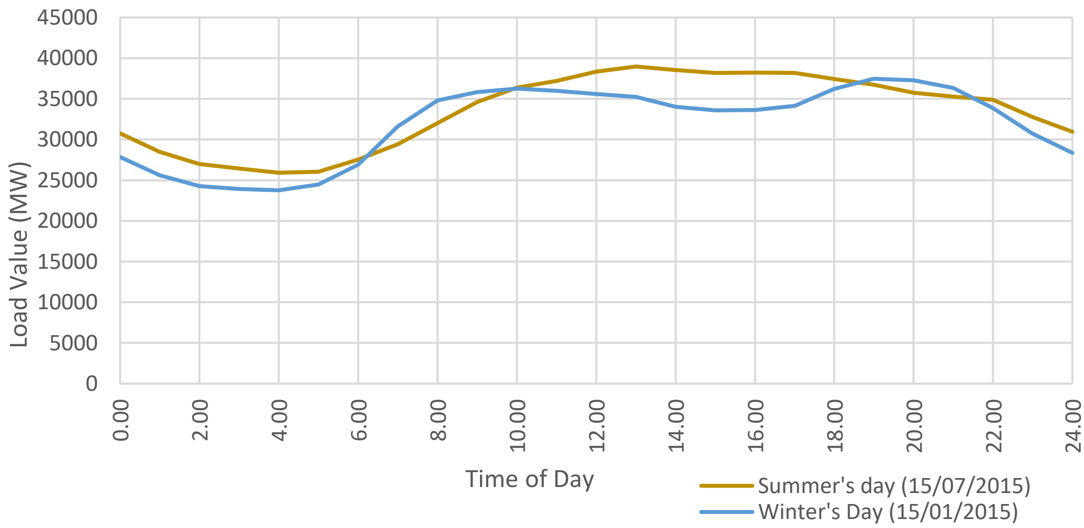


Figure 10 - Typical load profile for summer and winter day in Spain (46)

4.1.2 District Heating Fuel Mix

Eurostat energy balances were used to determine the current fuel mix of district heating systems in Finland, Germany and Poland, Figure 11. No data was available for the DH fuel mix in Spain on Eurostat, however an EC report producing case studies on effective DHC systems highlighted that the Spanish market is dominated by natural gas (42). Although Finland has the largest RES share of DH their fossil fuel mix contains comparatively large levels of peat; between 201ktoe (43) and 463ktoe (47). This will offer a large potential for emission reduction due to the high emission factor of peat.

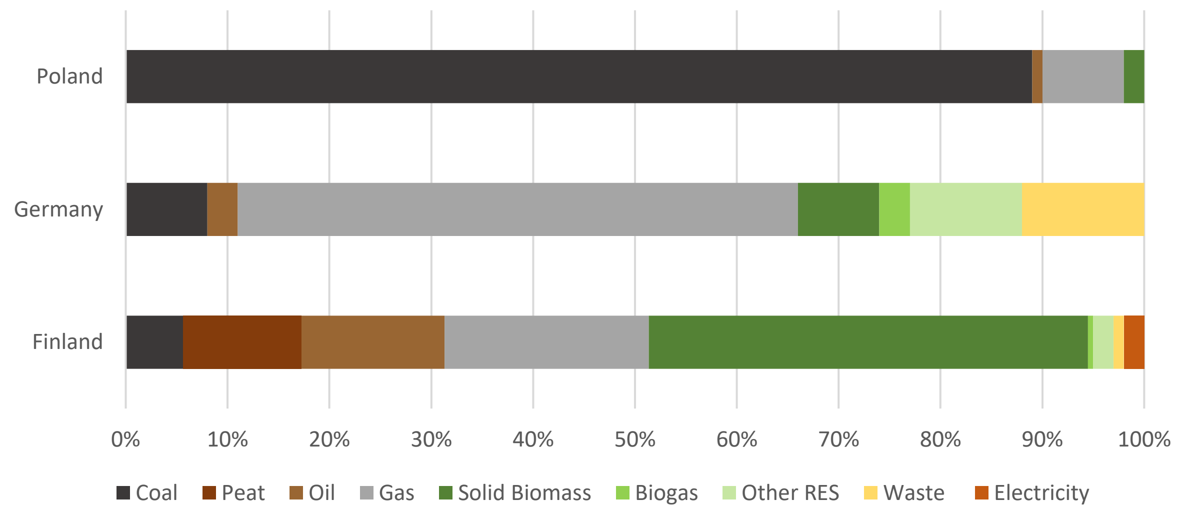


Figure 11 - District heating fuel mix for Finland, Germany and Poland, 2016 (43)

4.1.3 Available Resources

To determine the optimum use of bioheat within Europe the available resources must be understood. Eurostat databases were used to establish current wood and manure production, imports and exports, given in Table 5. The EU Atlas of Bioenergy has analysed the biomass potential in regard to a 2020 reference case and the major opportunities are highlighted in Figure 12. It is important to note that this potential falls across all energy vectors and some feedstock types will be highly regarded due to their potential in other areas such as for liquid biofuels.

Table 5 - Resources available for biomass production, 2017 (48) (49)

	Finland	Germany	Poland	Spain
Wood Pellet Production (1000 tonnes)	324	22590	900	461
Wood Pellet Imports (1000 tonnes)	87	391	74	42
Wood Pellet Exports (1000 tonnes)	37	451	339	117
Wood C,P&R Production (1000m^{3}s)	15433	14230	10199	3693
Wood C,P&R Imports (1000m^{3}s)	2844	2045	1608	63
Wood C,P&R Exports (1000m^{3}s)	199	2431	846	479
Roundwood Production (1000m^{3}s)	63279	53491	45348	17566
Roundwood Imports (1000m^{3}s)	4841	9074	1741	590
Roundwood Exports (1000m^{3}s)	977	4097	2964	1435
Manure Production (1000 tonnes)	13395	202013	98630	117766

*CP&R = chips, particles and residues

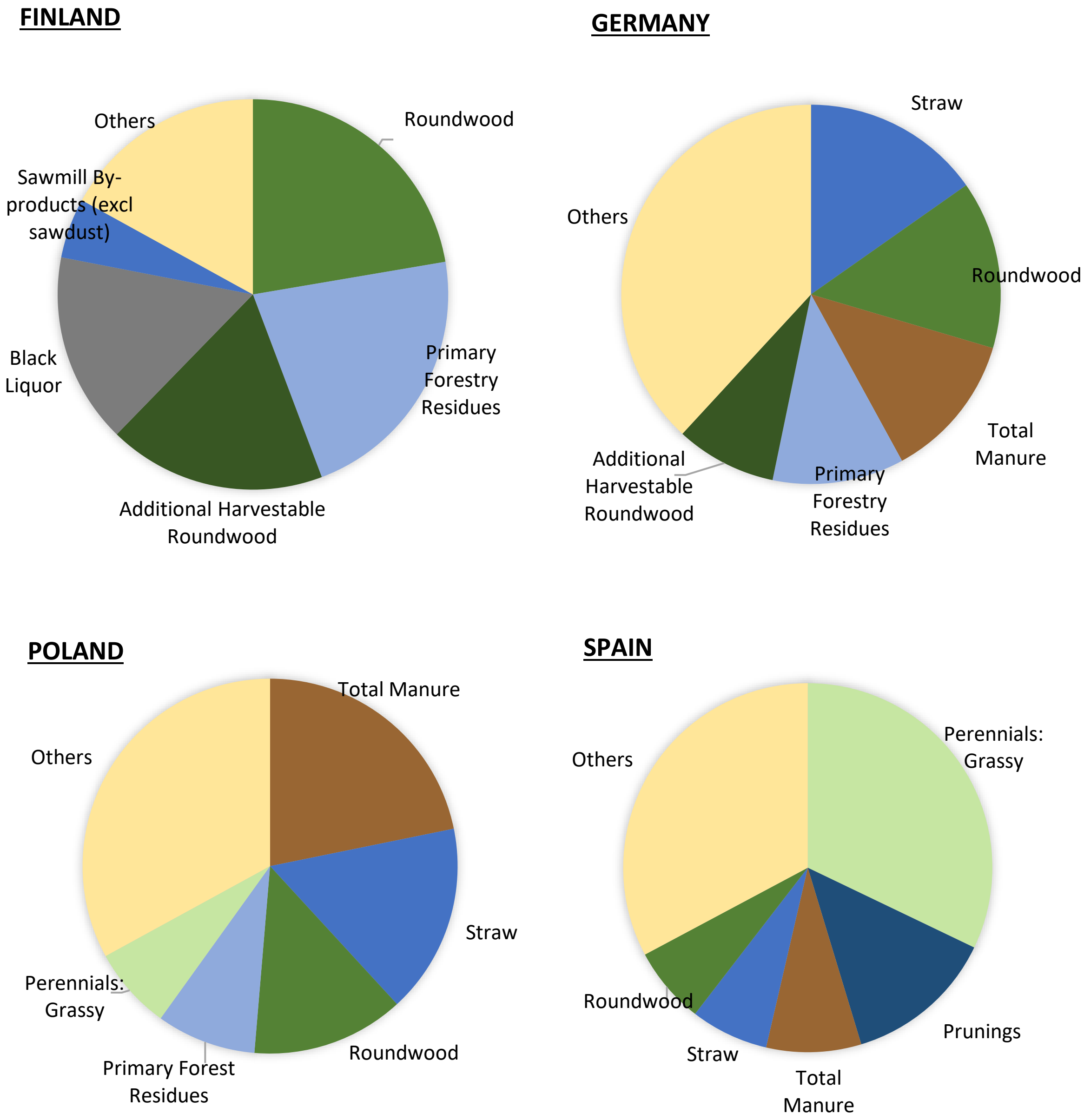


Figure 12 - Energy potential biomass source breakdown for (a) Finland, (b) Germany, (c) Poland and (d) Spain (50)

Finland, Germany and Poland have relatively similar outlooks focusing mainly on woody feedstock, straw and manure. The Spanish breakdown differs with grassy perennials and prunings accounting for over one third of total potential. This is likely to be largely cost driven, as the cost levels are much lower than that of woody crops in the Mediterranean due to climate and land type (50).

4.1.4 Costs

Cost data has been taken from the Atlas of EU biomass potentials and Table 6 shows the energy potential of each feedstock and associated cost for the top five feedstock types for each country as identified in section 4.1.3.

Table 6 - EU biomass potentials with associated cost for 2020 reference scenario (50)

	Feedstock Type	Reference scenario 2020	
		Ktoe	Euro/Toe
Finland	Roundwood	6297	496
	Primary Forestry Residues	6189	165
	Additional Harvestable Roundwood	5083	397
	Black Liquor	4449	0
	Sawmill By-products (excluding sawdust)	1400	116
Germany	Straw	8883	147
	Roundwood	8353	578
	Total Manure	7266	86
	Primary Forestry Residues	6537	231
	Additional Harvestable Roundwood	5015	463
Spain	Perennials: Grassy	10133	182
	Prunings	4164	36
	Total Manure	2622	100
	Straw	2153	122
	Roundwood	2128	578
Poland	Total Manure	8177	88
	Straw	6142	156
	Roundwood	4939	496
	Primary Forest Residues	3220	165
	Perennials: Grassy	2668	131

4.1.5 Political, social, economic and technological (PEST) analysis

A PEST analysis was conducted to highlight the key external factors that constitute potential barriers to the implementation of the optimal solution. A complete optimisation encompassing these factors was considered outside of the scope of this research, as it falls in a more multi-disciplinary field and would require more time. However, by noting these factors and considering them at a higher level they can be investigated in further research to gain a holistic appreciation of the system and its sensitivity to external influence.

Political

Different policies and levels of investment means uptake may be more difficult in some areas
Increased popularity of far-right politics within Europe causing political instability
Increasing pressures on fighting climate change including recent school pupil strikes and days of action
EU National renewable energy action plan RES targets

Social

Land-use debates
Negative press driving negative connotations towards bioenergy
Change in knowledge base – retraining or new workforces
Investment in bioenergy will create jobs

Economic
Economic reliance on exported coal may deter moves away from this - of particular relevance in Poland
Investment needed to grow district heating systems
Optimisation of scenarios with cost as the leading factor may appeal more
Technological
Growth of additional renewable technologies such as geothermal and heat pumps
Increased efficiencies possible to further improve environmental performance
Climate changes causing more extreme weather, which will affect demand predictions and models

In addition, existing EU targets set in response to the Renewable Energy Directive, are given in Table 7 to summarise current attitudes towards renewables. As of 2017, only Finland was already meeting 2020 targets. The EU wide target share of RES in FEC for 2030 was set at 27% and later raised to 32% despite opposition from Germany (51). National targets to meet this have not been set collectively, although individual governments may choose to do so.

Table 7 - EU National renewable energy action plan (NREAP) targets and current progress (52)

Country	NREAP Targets for 2020	Progress as of 2017
Finland	38% share of RES in FEC 47% share of RES in heating and cooling	41% share of RES in FEC 54.9% share of RES in heating and cooling
Germany	18% share of RES in FEC 15.5% share of RES in heating and cooling	15.5% share of RES in FEC 13.4% share of RES in heating and cooling
Poland	15% share of RES in FEC 17% share of RES in heating and cooling	10.9% share of RES in FEC 14.5% share of RES in heating and cooling
Spain	20% share of RES in FEC 18.9% share of RES in heating and cooling	17.5% share of RES in FEC 17.5% share of RES in heating and cooling

This analysis has guided a higher-level approach to analysing the risks to uptake, alongside basic justification, shown in Table 8. This can be used alongside the final optimisation results to appreciate additional challenges affecting the implementation of any recommendations.

Table 8 - Potential risks levels to implementing an increase of RES in DH

Country	Risk	Justification
Finland	Low	Already ahead of NREAP 2020 targets
Germany	Medium	Reasonable progress towards NREAP 2020 targets but objection to raising 2030 targets suggests some barriers
Poland	High	High economic reliance on exported coal and largest non-RES share of DH
Spain	Medium	Reasonable progress towards NREAP 2020 targets but requires improved monitoring by national body.

4.2 Emission Data

Following initial research, emission data was collected for the four chosen countries; Finland, Germany, Poland and Spain. This was done in a two tier approach, first using existing literature and second using a GHG calculation model.

4.2.1 Literature Based Results

Using a variety of existing studies and reports emission data was recorded for various feedstock options considering stages up to and including use in either combustion or anaerobic digestion (AD) plants. A wide range of values was observed, with maximum and minimum values shown in Table 9 and Figure 13. These differences are driven by variations in conversion process, location, system boundaries and scope of study. When only one of the data sources from Table 9 was used, the variation was, on the most part, seen to decrease; highlighted in Figure 14. As a result, this research will use a single tool to collect the emission data required to perform the optimisation. The BioGrace II tool has been chosen to ensure consistent system boundaries with data that is relevant to EU countries.

Table 9 - GHG emission ranges from literature

Feedstock	GHG Emissions (gCO2eq/MJ)	References
Forest Residues	1.9-22.7	(53), (54)
Roundwood	5.5-102	(55), (56)
Wood Chips	0.0-45.7	(55)
Wood Pellets	9.9-50.7	(55)
Miscanthus	5.0-45.0	(57), (55)
Straw	11.06-83.3	(58)
Agricultural Residues	4.3-15.5	(55)
AD Biogas	5.1-63.8	(55), (56)

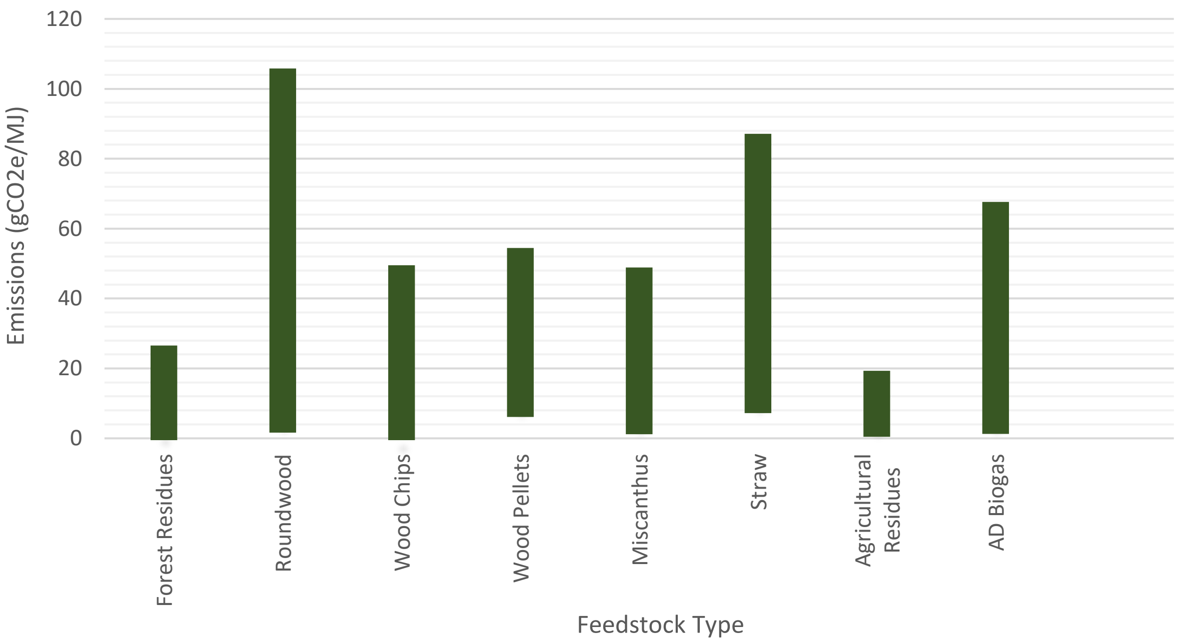


Figure 13 - Feedstock emission range with multiple data sources

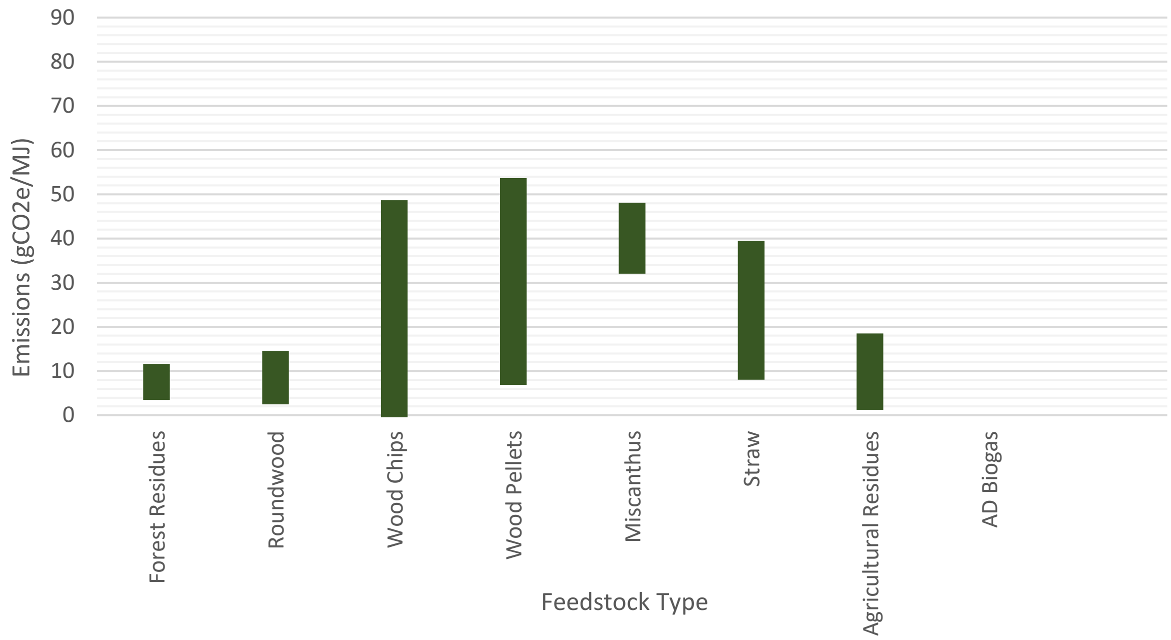


Figure 14 - Feedstock emission range using one data source

4.2.2 BioGrace II Results

To collect the main body of data for the optimisation process, 310 scenarios were simulated with the BioGrace tool. These reflected the potential feedstock options for each country, given in Figure 12, and considered the alternative fuels as set out in Figure 11. The data can be analysed in a number of ways and will be analysed first by feedstock, and then by country. The full database is available in the supporting document to this report.

First, analysis was performed to establish the maximum and minimum values for each feedstock (Figure 15) and ensure these fell within the reasonable values previously identified. This aims to corroborate the data and validate the collection process whilst providing an overall indication of the performance of each feedstock.

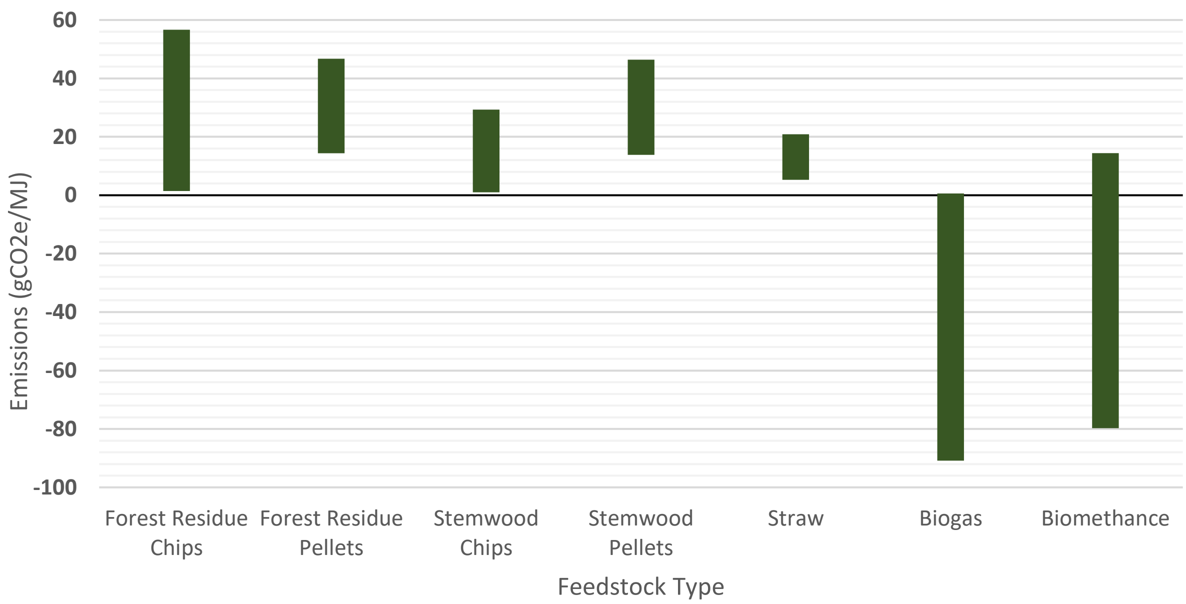


Figure 15 - Feedstock emission range from BioGrace II for the 310 scenarios modelled

Secondly, the effect of distance was explored. The emission reduction would be expected to decrease with increased transportation distance due to the increased emissions associated with fuelling this. This was explored for all feedstock types in combustion systems in Poland with substitution for coal, and the effects of changing distance can be seen in Figures 16a-16c. Not only does emission reduction decrease with increased transportation distance, but the variation between CHP and heat only systems can be seen to increase.

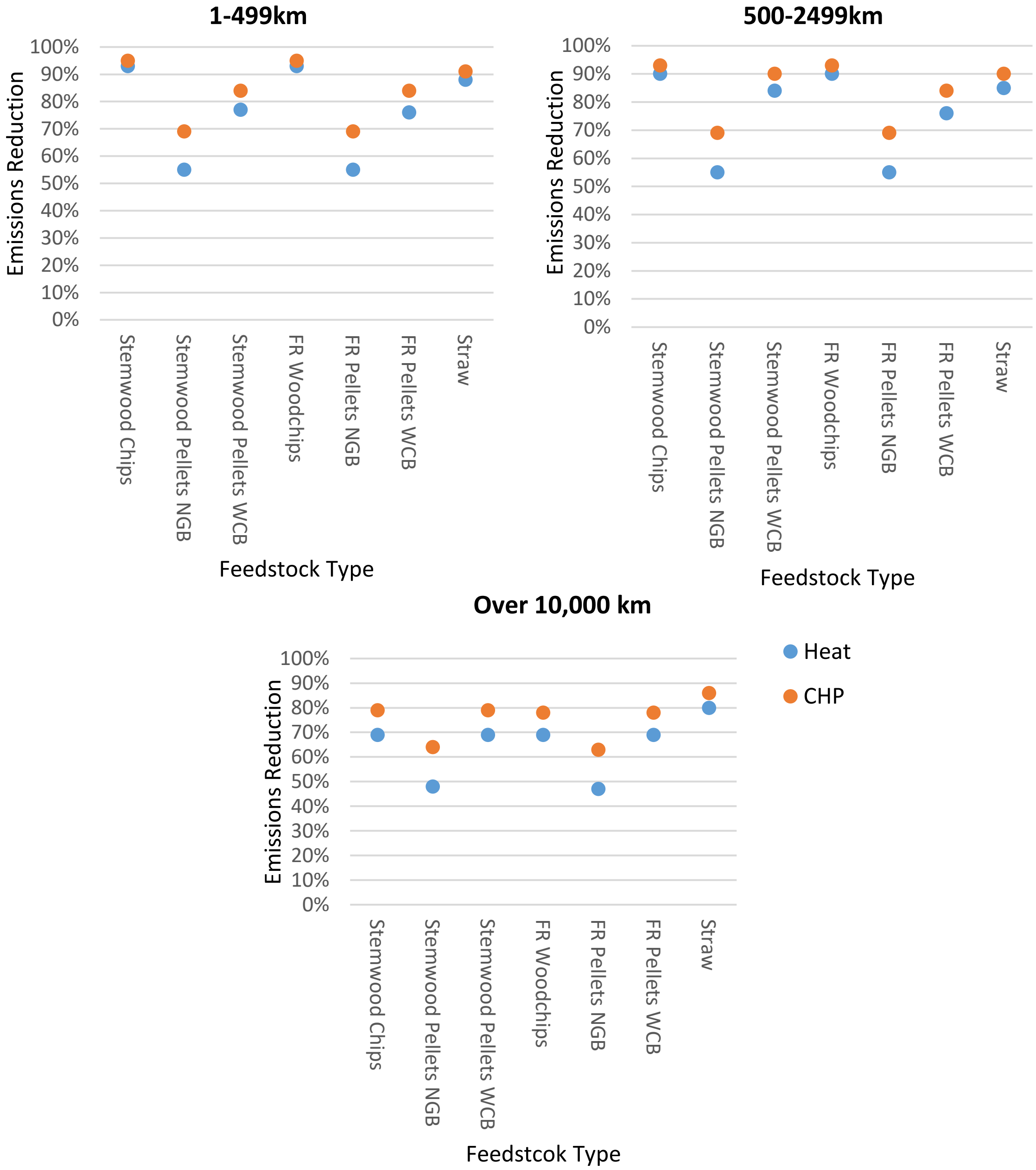


Figure 16 - Emission reduction for biomass combustion with both heat only and CHP output for (a) 1-500km, (b) 500-2499km and (c) over 10,000km

When considering the individual, environmental performance of each country the best eight and worst eight scenarios were tabulated[2] to explore the key influencing factors. These were ranked according to their emission reduction potential. Tables 10 through 16 display this data.

FINLAND

Table 10 - GHG emission data for Finland; top 8 scenarios for emission reduction

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
SWC	Peat	CHP	1-499	5.03	0.01	0	5.6	96
FRC	Peat	CHP	1-499	5.41	0.01	0	6.0	95
FRC	Coal	CHP	1-499	5.41	0.01	0	6.0	95
SWC	Coal	CHP	1-499	5.03	0.01	0	5.6	95
FRC	Peat	Heat	1-499	5.41	0.01	0	6.0	94
FRC	Peat	CHP	500-2500	7.68	0.01	0	8.2	94
SWC	Peat	Heat	1-499	5.03	0.01	0	5.6	94
SWC	Peat	CHP	500-2500	7.30	0.01	0	7.8	94

Table 11 - GHG emission data for Finland; bottom 8 scenarios for emission reduction

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
FRP NGB	Coal	Heat	10,000+	39.28	0.09	0	42.2	49
SWP NGB	Coal	Heat	10,000+	38.92	0.09	0	41.8	49
FRP NGB	Peat	Heat	10,000+	39.28	0.09	0	42.2	54
FRP NGB	Coal	Heat	2500-10,000	35.04	0.09	0	37.9	54
SWP NGB	Coal	Heat	2500-10,000	34.68	0.09	0	37.6	54
SWP NGB	Peat	Heat	10,000+	38.92	0.09	0	41.8	55
FRP NGB	Coal	Heat	1-499	33.34	0.09	0	36.2	56
FRP NGB	Coal	Heat	500-2500	33.22	0.09	0	36.1	56

When looking at Tables 10 and 11 it can be seen that for Finland replacing bioenergy use for peat will create, in most cases, the greatest emission reductions. Similarly, use in CHP systems is preferential to heat only systems, and distance should be minimised for maximum environmental benefit. The worst performing scenarios involved pellet feedstock with a natural gas boiler for heat provision during pellet production and a heat only output. A variety of transportation distances can be seen suggesting this is not the major influencing factor. Methane emissions are much higher in the worse performing cases reflecting the large global warming potential of this GHG. The overall range of reduction is from 49% to 96%.

[2] Section specific acronyms; SWC: stemwood chips, SWP: stemwood pellets, FRC: forest residue chips, FRP: forest residue pellets, NGB: natural gas boiler, WCB: wood chip boiler

GERMANY

Table 12 - GHG emission data for Germany; top 8 scenarios for emission reduction

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
Manure	Coal	CHP	500	90.62	-3.03	-0.07	-4.0	Over 100
Manure	Natural Gas	CHP	500	90.62	-3.03	-0.07	-4.0	Over 100
SWC	Coal	CHP	1-499	5.03	0.01	0	5.6	95
FRC	Coal	CHP	1-499	5.41	0.01	0	6.0	94
SWC	Coal	CHP	500-2500	7.30	0.01	0	7.8	93
SWC	Natural Gas	CHP	1-499	5.03	0.01	0	5.6	92
FRC	Coal	Heat	1-499	5.41	0.01	0	6.0	92
SWC	Coal	Heat	1-499	5.03	0.01	0	5.6	92

Table 13- GHG emission data for Germany; bottom 8 scenarios for emission reduction

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
FRP NGB	Natural Gas	Heat	10,000+	39.28	0.09	0	42.2	11
SWP NGB	Natural Gas	Heat	10,000+	38.92	0.09	0	41.8	12
FRP NGB	Natural Gas	Heat	2500-10000	35.04	0.09	0	37.9	20
SWP NGB	Natural Gas	Heat	2500-10000	34.68	0.09	0	37.6	21
FRP NGB	Natural Gas	Heat	1-499	33.34	0.09	0	36.2	24
FRP NGB	Natural Gas	Heat	500-2500	33.22	0.09	0	36.2	24
SWP NGB	Natural Gas	Heat	500-2500	32.86	0.09	0	35.8	25
SWP NGB	Natural Gas	Heat	1-499	32.98	0.09	0	35.9	25

Table 12 highlights the best scenario for reducing GHG emissions in Germany is anaerobic digestion of manure. This is due to the manure credit implemented within the BioGrace tool to account for improved manure management that results in negative total equivalent emissions for a transportation distance of 500km. The table also highlights that CHP is preferable to a heat only output and scenarios that replace coal result in greater emission reductions than those which replace natural gas. Table 13 highlights again that the worst performing scenarios use pellet feedstock created with a natural gas boiler for heat provision during pellet production and a heat only output with an alternative fuel of natural gas. All 8 scenarios share these features with distance and choice between stemwood and forest residues being less influential considerations. The potential emission reduction for all scenarios ranges from 11% to over 100%.

POLAND

Table 14- GHG emission data for Poland; top 8 scenarios for emission reduction

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
Manure	Coal	CHP	500	90.62	-3.03	-0.07	-4.0	Over 100
SWC	Coal	CHP	1-499	5.03	0.01	0	5.6	95
FRC	Coal	CHP	1-499	5.41	0.01	0	6.0	95
SWC	Coal	Heat	1-499	5.03	0.01	0	5.6	93
FRC	Coal	Heat	1-499	5.41	0.01	0	6.0	93
SWC	Coal	CHP	500-2500	7.30	0.01	0	7.8	93
FRC	Coal	CHP	500-2500	7.68	0.01	0	8.2	93
Straw	Coal	CHP	1-499	9.15	0.02	0	9.9	91

Table 15 - GHG emission data for Poland; bottom 8 scenarios for emission reduction

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
FRP NGB	Coal	Heat	10,000+	39.28	0.09	0	42.2	47
SWP NGB	Coal	Heat	10,000+	38.92	0.09	0	41.8	48
FRP NGB	Coal	Heat	2500-10000	35.04	0.09	0	37.9	53
SWP NGB	Coal	Heat	2500-10000	34.68	0.09	0	37.6	53
FRP NGB	Coal	Heat	500-2500	33.22	0.09	0	36.1	55
SWP NGB	Coal	Heat	500-2500	32.86	0.09	0	35.8	55
FRP NGB	Coal	Heat	1-499	33.34	0.09	0	36.2	55
SWP NGB	Coal	Heat	1-499	32.98	0.09	0	35.9	55

Table 14 shows anaerobic digestion of manure as the most environmentally beneficial scenario for Poland, followed by woodchip substituting coal in CHP when feedstock is transported under 500km. This is closely followed by the same scenario with a heat only output or with CHP output and a transportation distance of 500-2499km all at 93% emission reduction. Similar to the case for Germany and Finland, the worst performing scenarios involve pellet use as an alternative to coal with natural gas boilers providing the heat during production and an output of heat only. The emission reduction ranges from 47% to over 100%.

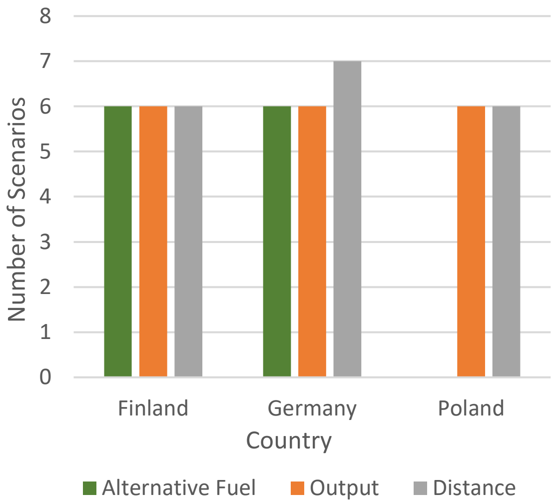
SPAIN

Table 16 - GHG emission data for Spain; best and worse scenarios

Feedstock	Alternative Fuel	Output	Distance (km)	gCO2	gCH4	gN20	Total (gCO2eq)	Reduction (%)
Manure (biogas)	Natural Gas	CHP	500	90.62	-3.03	-0.07	-4.0	Over 100
Straw	Natural Gas	CHP	1-499	9.15	0.02	0	9.9	85
Manure (biomethane)	Natural Gas	Injected	500	98.66	-2.76	-0.07	9.8	83
Straw	Natural Gas	CHP	500-10000	11.03	0.02	0	11.8	82
Straw	Natural Gas	Heat	1-499	9.15	0.02	0	9.9	76
Straw	Natural Gas	CHP	10,000+	15.47	0.02	0	16.3	75
Straw	Natural Gas	Heat	500-10000	11.03	0.02	0	11.8	72
Straw	Natural Gas	Heat	10,000+	15.47	0.02	0	16.3	61

Due to the limited number of scenarios that represented the potential feedstock types of Spain, best and worse results are visible in Table 16 and show a range of emission reduction from 61% to over 100%. Manure for use as biogas is the top-performing scenario; however when used for biomethane, with a transportation distance of 500km the scenario is outperformed by straw. This is likely to be due to the use of natural gas as an alternate fuel that limits the reduction potential compared to fossil fuels with a higher emission factor such as peat and coal. The best use of straw was in CHP systems with minimal transportation, and the worst performing case for Spain is to use straw in a heat only system with a feedstock transportation distance over 10,000km.

When considering only emission reduction there are a number of influencing factors including feedstock type, alternative fuel, output and transportation distance. Figures 17 and 18 give a representation of the importance of each factor for the best and worst eight scenarios by showing the frequency of traits with lowest or highest associated emissions respectively. Feedstock type has not been included in the best scenarios as not all manure scenarios were included, and had this been the case all top eight scenarios would be AD processes using manure.



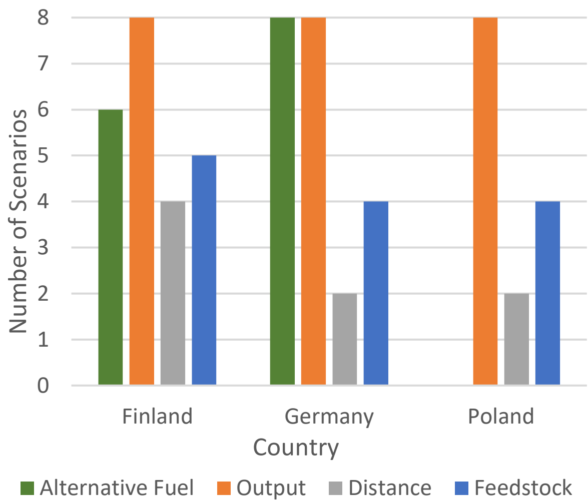


Figure 17 - Prevalence of influencing factors for the best eight scenarios (left)

Figure 18 – Prevalence of influencing factors for the worst eight scenarios (right)

4.3 Optimisation Results

To give an appreciation of the multi-faceted nature of biomass, and to acknowledge that policy often has competing drivers a MCO optimisation has been performed to consider both economic and environmental impact. Full data sets can be found in the accompanying document and key findings are outlined below. The filter excel function can be used to optimise with regard to a single factor, such as emission reduction or cost, and results can be viewed in a single list. When sorted by emission reduction only, AD process were the best, ranked equally for each country due to the constraints imposed. However the actual reduction will be greater when substituted for peat or coal and transported over shorter distances. The top performing combustion scenario, with an emission reduction of 96%, was the use of stemwood chips in Finland for CHP, substituting for coal with transport distances of 1-499km. The lowest performing scenario was forest residue pellets produced using a natural gas boiler and transported over 10,000km used for heat only and substituting for natural gas with a reduction of 11%.

4.3.1 Visual Representation of Performance

Initially the emission results were considered alongside cost and availability data given in Table 6. To visualise performance, bubble charts have been created demonstrating the performance of each feedstock-conversion partnership with regard to emission reduction and cost (Figures 19-26). The scenarios performing well in both will be those with a high potential for emission reduction at a low cost and will sit in the bottom right quarter of the graph. As a scenario performs worse in these economic and environmental indicators the bubble will move up and left respectively. The size of the bubble is proportional to the potential levels of this feedstock, with large bubbles representing sources with great energy potential. Feedstock groups have been combined in colour groups with different shades of a colour representing a different conversion method or output and have been performed on a country-by-country basis.

FINLAND

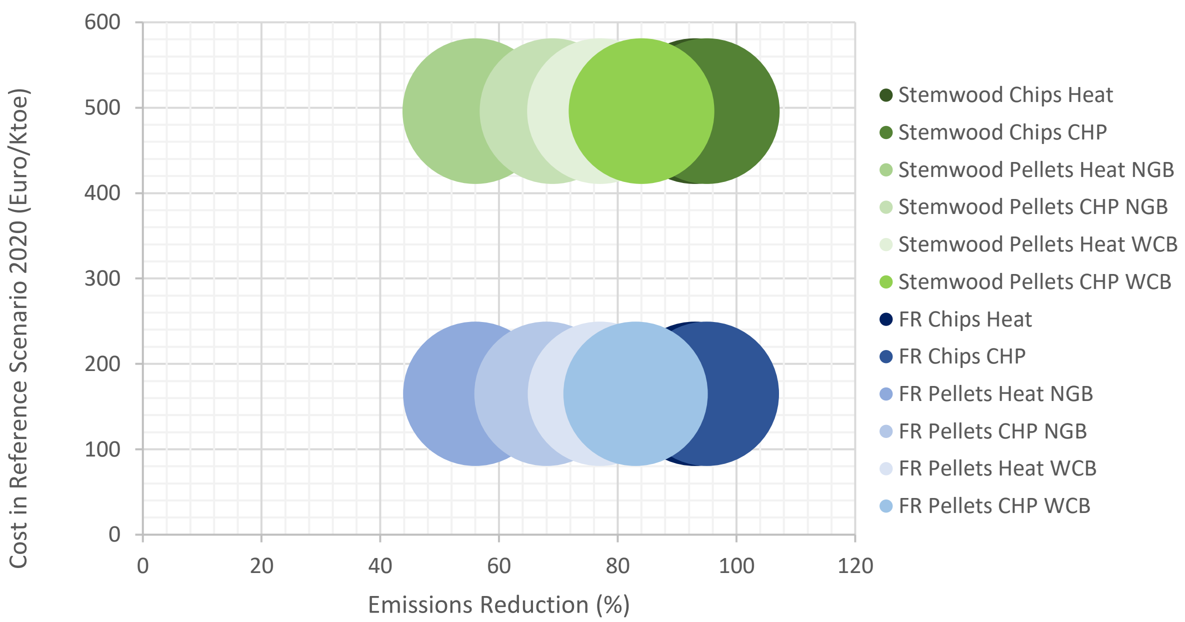


Figure 19 - Feedstock and conversion technology options in Finland substituting for coal

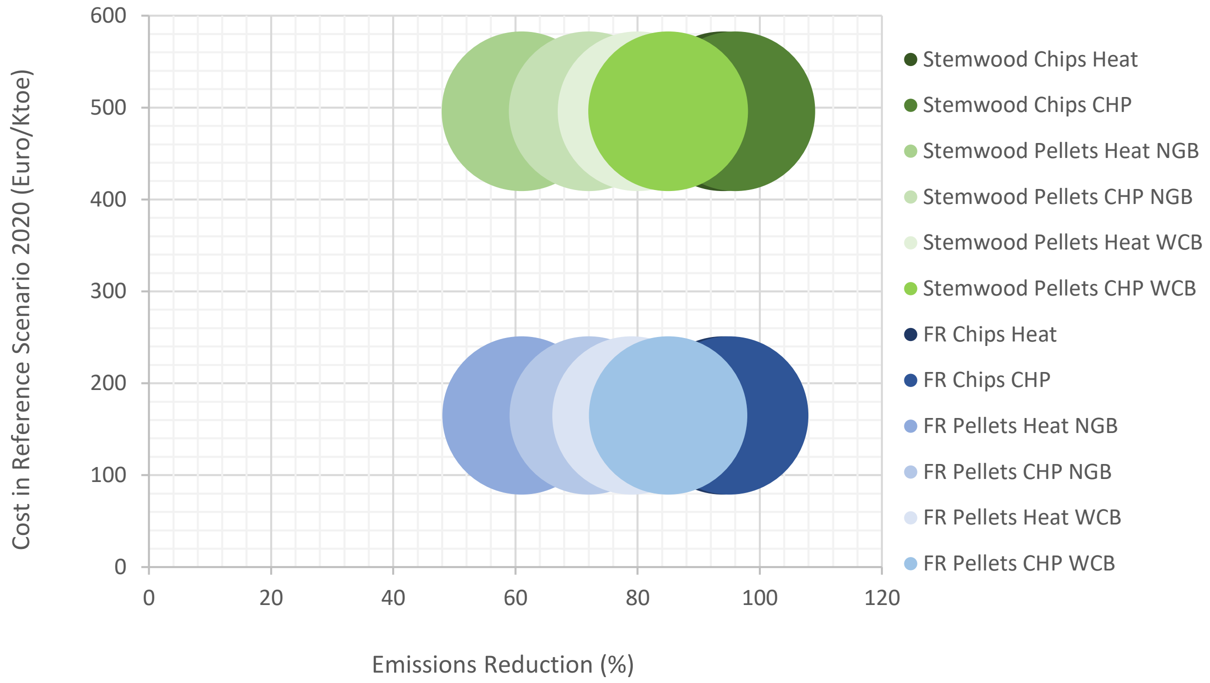


Figure 20 - Feedstock and conversion technology options in Finland substituting for peat

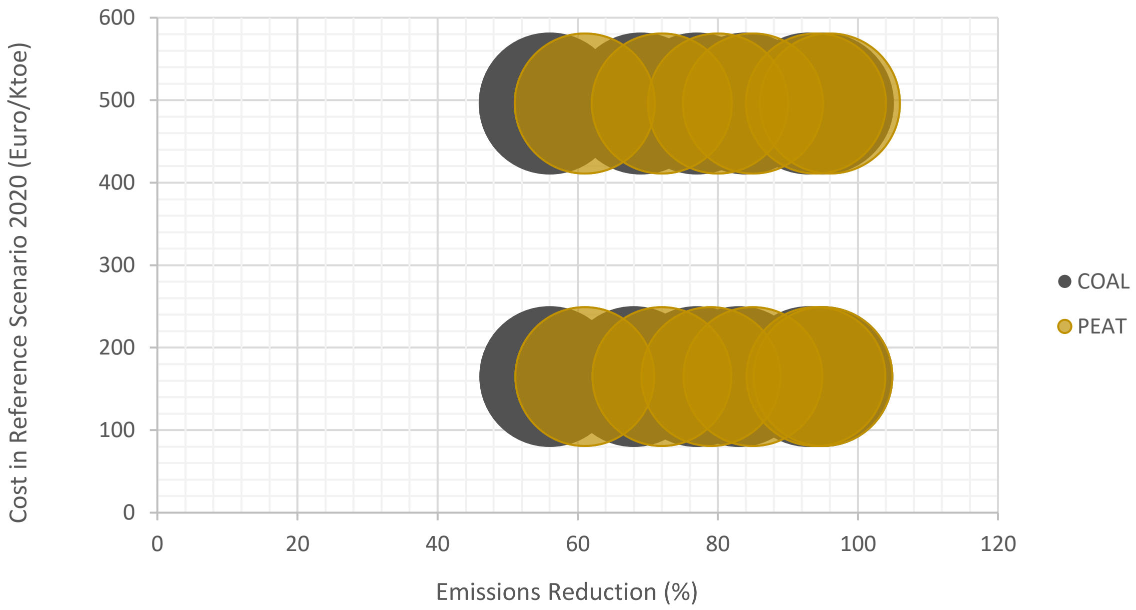


Figure 21 - Comparison of emission reduction substituting for coal or peat in Finland

Figures 19 and 20 demonstrate that for Finland both forest residues and stemwood perform similarly from an environmental perspective, however from an economic perspective forest residues would be the preferable feedstock. Figure 21 highlights the opportunity to increase emission reduction when substituting for peat instead of coal.

GERMANY

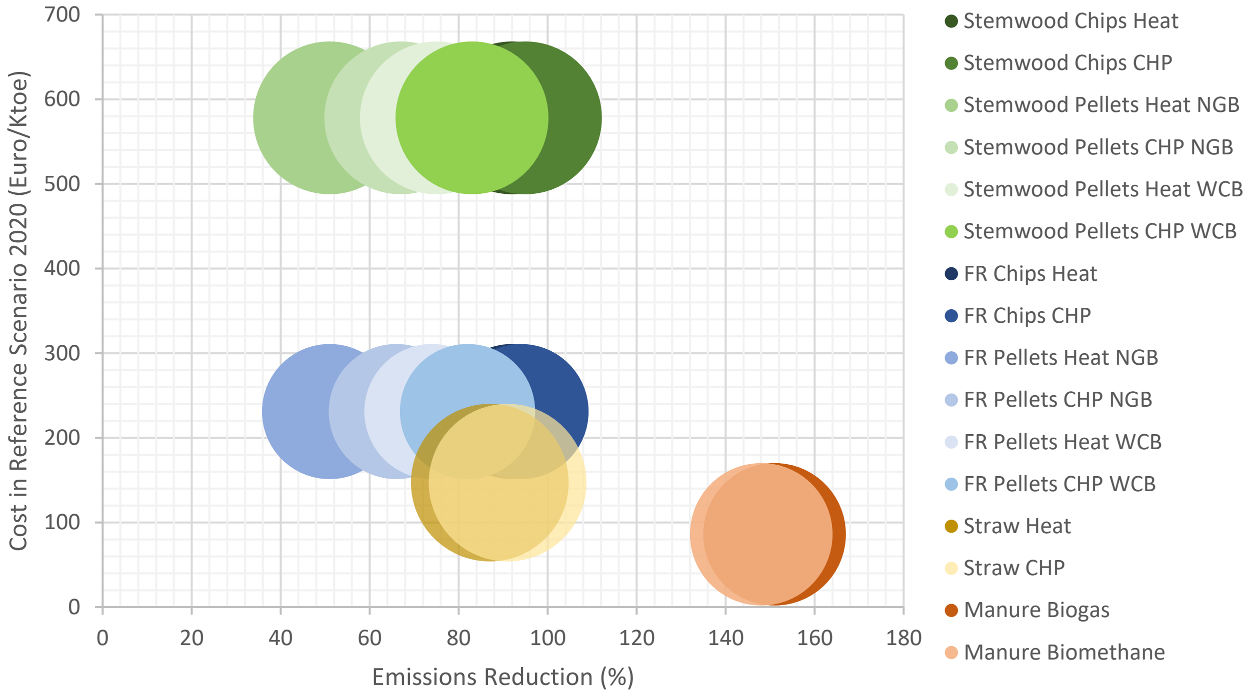


Figure 22 - Feedstock and conversion technology options in Germany substituting for coal

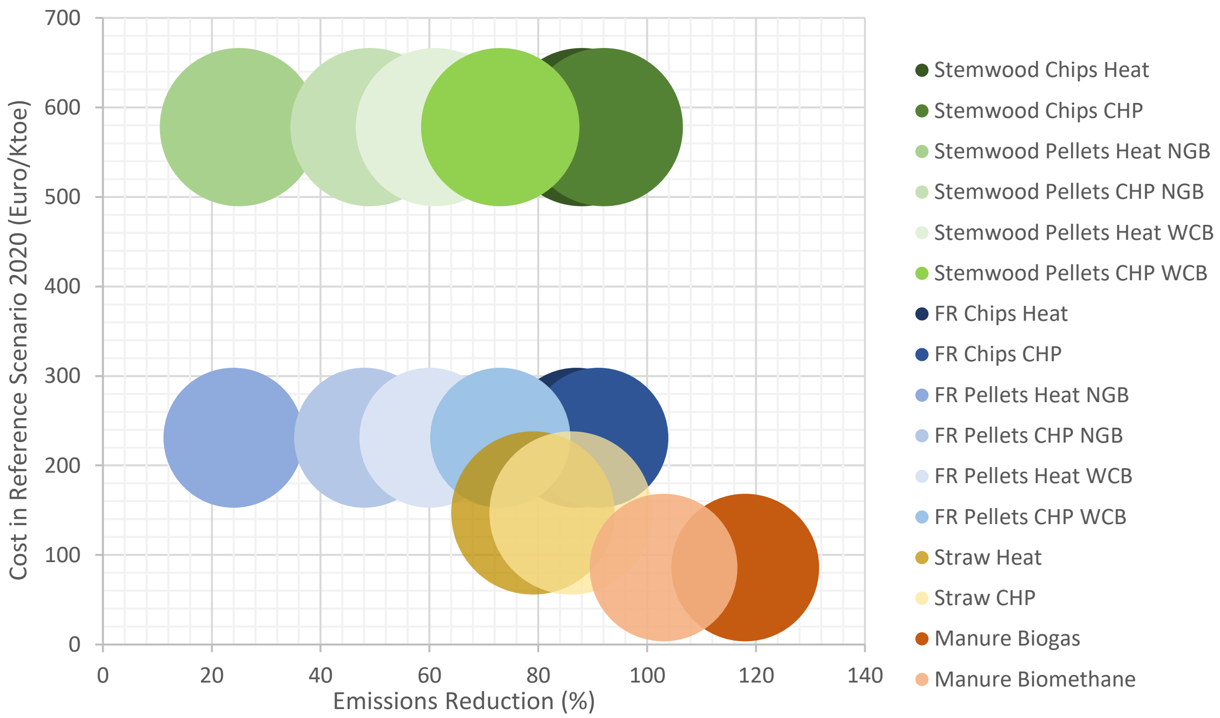


Figure 23 - Feedstock and conversion technology options in Germany substituting for natural gas

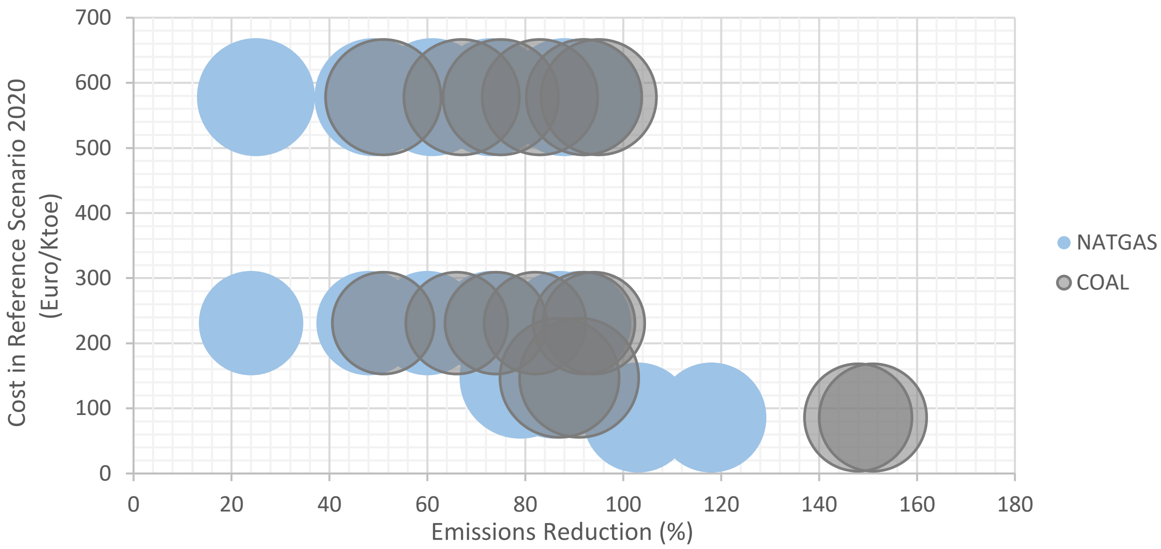


Figure 24 - Comparison of emission reduction substituting for coal or natural gas in Germany

Figures 22 and 23 show that for Germany the feedstock with a high emission reduction ability, and low cost are also predicted to have the greatest potential in the 2020 reference scenario as seen by the large bubbles in the lower right quadrant for straw and manure scenarios. This is a positive result and is expected to be reflected in the mathematical MCO results. Figure 24 demonstrates the difference in emission reduction when substituting for coal or natural gas.

POLAND

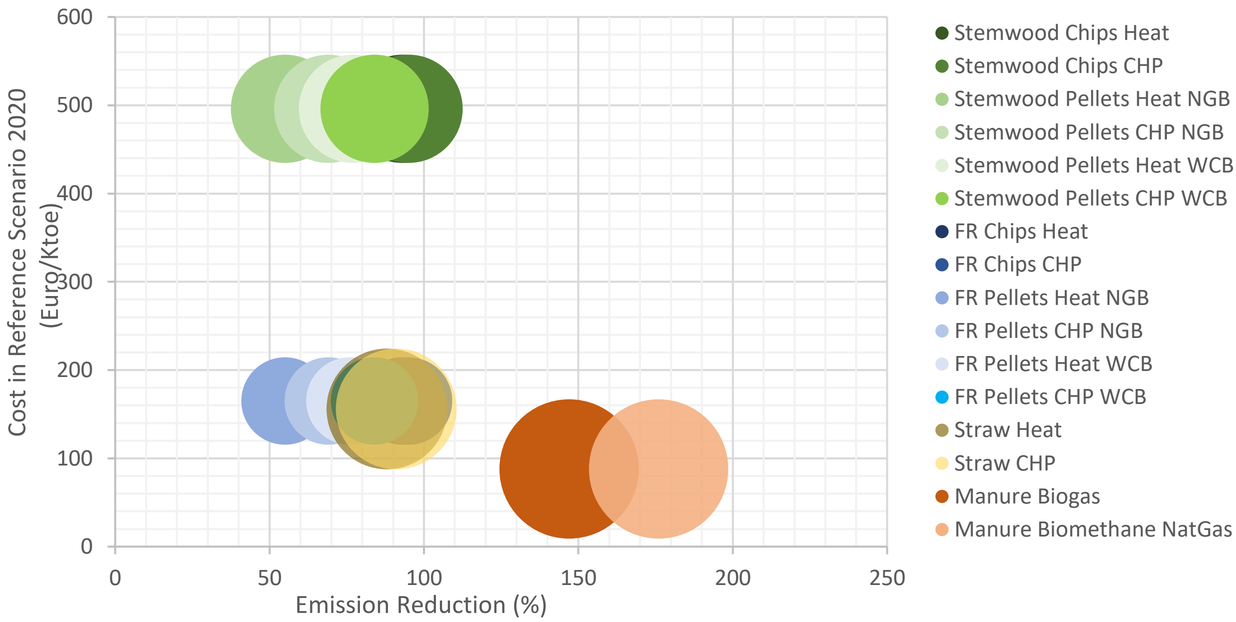


Figure 25 - Feedstock and conversion technology options in Poland substituting for coal

As coal was the only alternative fuel considered in Poland, Figure 25 displays the data for all scenarios considered over a set distance. It demonstrates that the feedstock types performing well in both environmental and economic objectives (manure and straw) have high energy potentials. Although the cost of forest residues is below that of stemwood, its potential is also lower which may prevent it from offering a large scale, long-term solution.

SPAIN

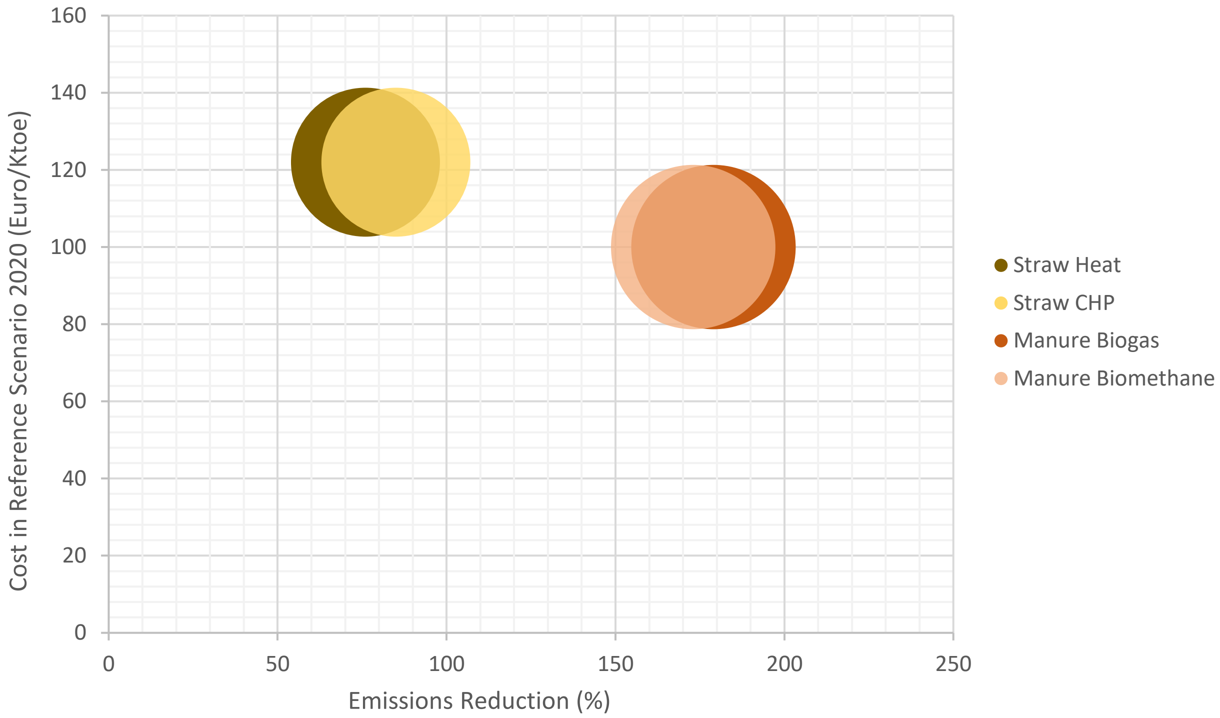


Figure 26 - Feedstock and conversion technology options in Spain substituting for natural gas

Due to the limited feedstock selection in the BioGrace tool, Figure 26 adds little to the analysis beyond that which can be obtained from Table 16 but has been included for completeness.

4.3.2 Comparison of Objective Function Equations

Two equations were created: equation 1 employing a linear optimisation method; and equation 2 a non-linear approach. Each objective function aims to minimise the final value and results can then be filtered in ascending order to rank the scenarios from 1 (best) to 310 (worst). First, method 1 was run and the scenarios were numbered from 1 to 310 based on their performance. The scenarios were then run through method 2 and the new ranking for each scenario number was recorded. Figure 27 demonstrates the difference in performance with orange marks below the green line representing scenarios in which a better ranking was achieved with equation 2, and marks above the line where equation 2 achieved a worse result than equation 1. This demonstrates the variation in optimisation that can occur due to the choice of objective function.

$$f = \left((1 - E_R) + E_{EQ}\right) + \frac{Cost}{10} \qquad [1]$$

$$f = \left(\frac{1}{E_R} \times E_{EQ}\right) + \frac{Cost \times Potential}{10^6} \qquad [2]$$

Where: E_R *= Reduction in emissions (%)*
E_{EQ} *= Total GHG emissions (gCO$_2$eq)*

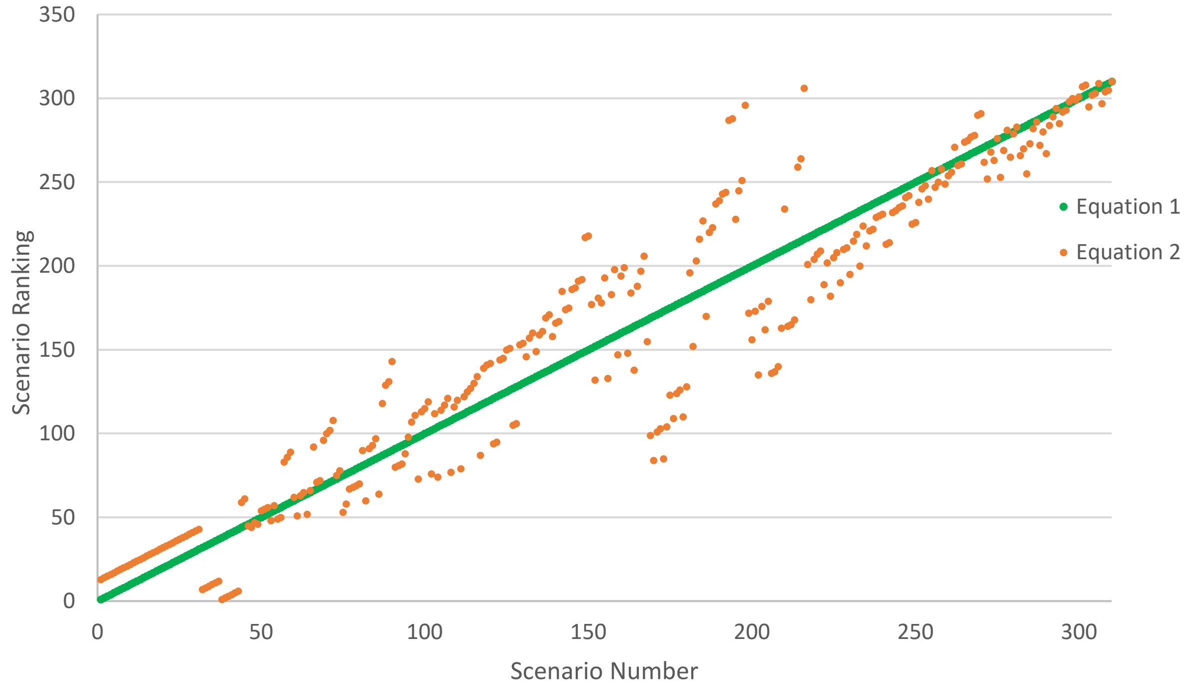


Figure 27 - Comparison of optimisation results for linear and nonlinear objective functions

To investigate this further, both scenarios were compared to two test cases, which numbered the scenarios based on their performance in a single factor optimisation against (i) emission reduction and (ii) cost. This was used to create two plots, Figures 28 and 29, which can be used to determine how methods 1 and 2 weight the environmental and economic components of the optimisation. The results that more closely follow the reference case demonstrate an affinity to this component in the optimisation.

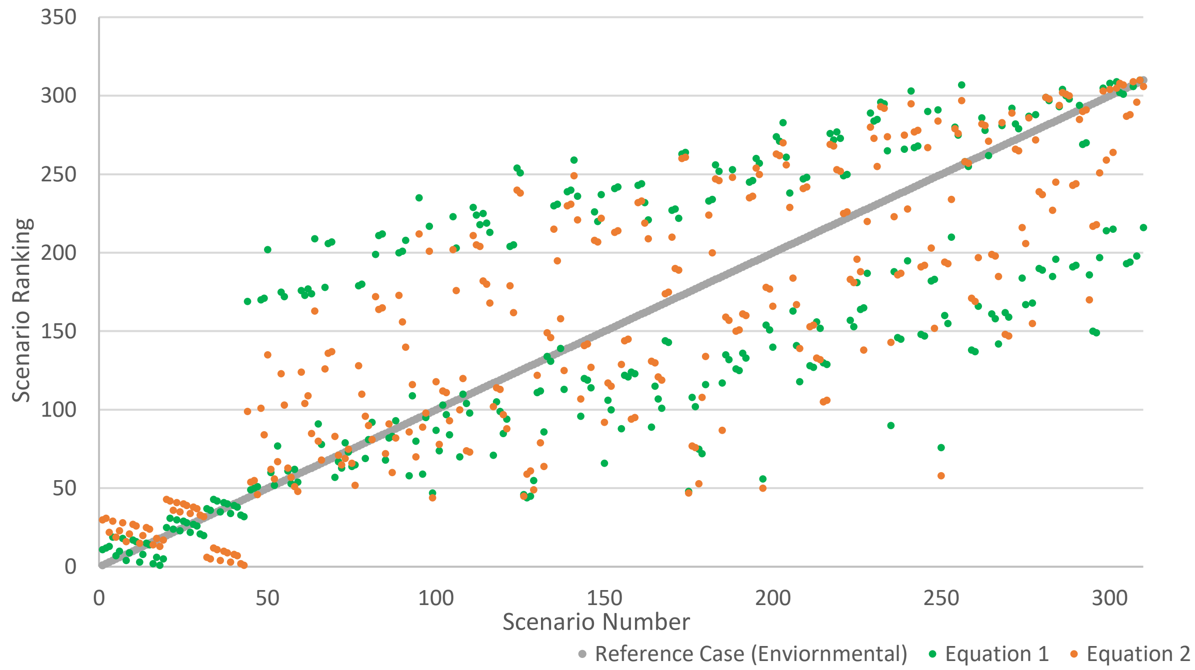


Figure 28- Comparison of objective function performance against environmental optimisation

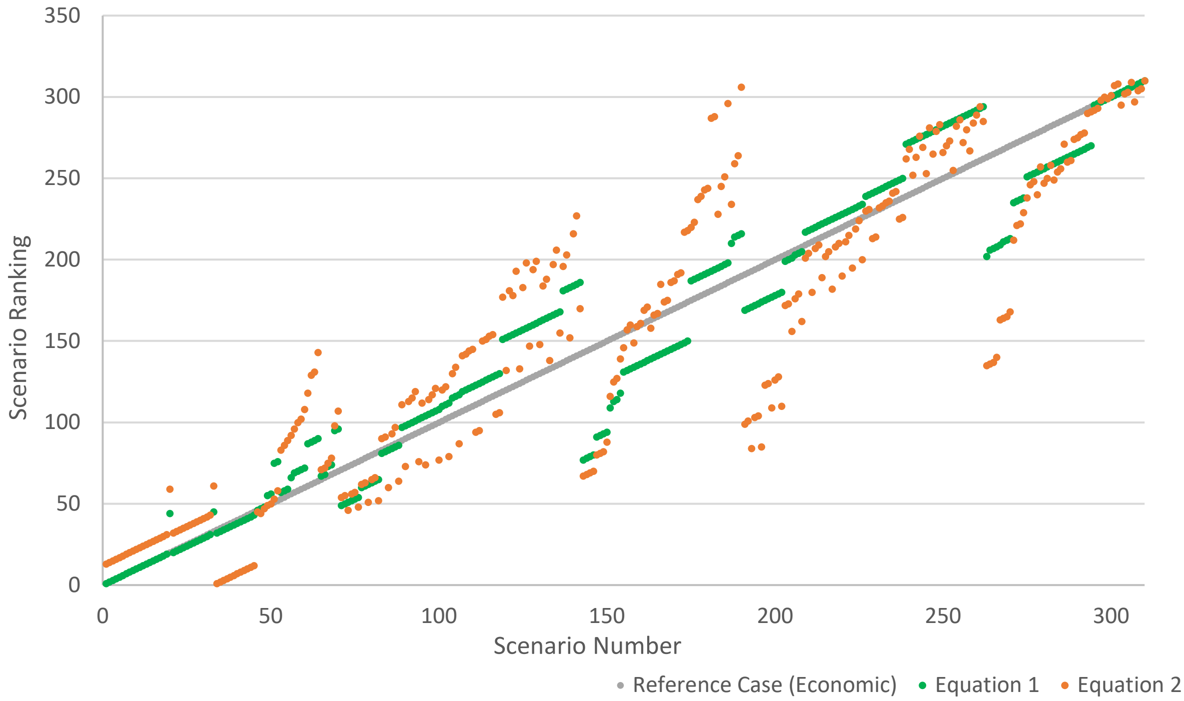


Figure 29 - Comparison of objective function performance against economic optimisation

Since the primary objective of this research is to consider environmental impact, further analysis has been conducted using the non-linear objective function (equation 2) as this follows the environmental reference case more closely.

4.3.3 Breakdown of Results

The best and worst 8 scenarios were found by sorting the optimisation output value in ascending and descending order respectively. Scenarios with optimisation values below one were not included as they were affected by the constraints imposed and outputted values of 0.26 in Spain, 0.62 in Germany and 0.72 in Poland. This means that the best 8 performing scenarios are not given in Table 17 as all of the best 8 scenarios outputted optimisation values below 1. Instead the 8 scenarios here allow for an analysis of additional factors that perform well. It should be noted that all scenarios producing biogas from AD of manure, and those producing biomethane with a transportation distance of under 500km, have been affected by this. Table 18 gives the worst 8 performing scenarios.

Table 17 - Top 8 scenarios when discounting optimisation values under 1

Country	Feedstock	Alternative Fuel	Output	Distance (km)	Emission Reduction (%)	Cost (Euro/Toe)	Optimisation Value
Spain	Straw	Natural Gas	CHP	1-499	85	122	3.1
Spain	Manure (biomethane)	Natural Gas	Injected	500	83	100	3.1
Poland	FRC	Coal	CHP	1-499	95	165	3.4
Spain	Straw	Natural Gas	Heat	1-499	76	122	3.4
Poland	FRC	Coal	Heat	1-499	93	165	3.4
Spain	Straw	Natural Gas	CHP	500-10000	82	122	3.8
Spain	Straw	Natural Gas	Heat	500-10000	72	122	4.3
Poland	FRC	Coal	CHP	500-2499	93	165	4.7

Table 18 - Bottom 8 scenarios when discounting optimisation values under 1

Country	Feedstock	Alternative Fuel	Output	Distance (km)	Emission Reduction (%)	Cost (Euro/Toe)	Optimisation Value
Germany	SWP NGB	Natural Gas	Heat	10000+	12	578	1682.8
Germany	SWP NGB	Natural Gas	Heat	2500-10000	21	578	864.4
Germany	SWP NGB	Natural Gas	Heat	1-499	25	578	693.3
Germany	SWP NGB	Natural Gas	Heat	500-2499	25	578	691.4
Germany	FRP NGB	Natural Gas	Heat	10000+	11	231	579.3
Germany	SWP NGB	Natural Gas	CHP	10000+	40	578	504.5
Germany	SWP NGB	Coal	Heat	10000+	43	578	469.3
Germany	SWP NGB	Natural Gas	CHP	2500-10000	46	578	394.6

The previously top performing scenario when ranked by emission reduction moved to 99th due to the comparatively high feedstock costs. If equation 1 were to be used this scenario drops even further to 169th which shows the extent to which economic factors can influence choices and how important it is to consider decisions in a multifaceted manner.

To further compare the results of the optimisation, the top 8 scenarios (again discounting those with optimisation values below 1) for each country have been found and are displayed in Tables 19-22. These results have been compared to the equivalent tables in 4.2.2 BioGrace II Results and where a scenario appears in both tables, it has been highlighted in green. Worst performing scenarios have not been investigated as the overarching aim is to reach a recommendation into the optimum use of biomass.

FINLAND

Table 19 - Optimisation data; top 8 scenarios for Finland discounting optimisation values below 1

Feedstock	Alternative Fuel	Output	Distance (km)	Emission Reduction (%)	Cost (Euro/Toe)	Optimisation Value
FRC	Peat	CHP	1-499	95	165	6.4
FRC	Coal	CHP	1-499	95	165	6.4
FRC	Peat	Heat	1-499	94	165	6.5
FRC	Coal	Heat	1-499	93	165	6.6
FRC	Peat	CHP	500-2499	94	165	8.9
FRC	Coal	CHP	500-2499	93	165	9.0
FRC	Peat	Heat	500-2499	91	165	9.2
FRC	Coal	Heat	500-2499	90	165	9.3

GERMANY

Table 20 - Optimisation data; top 8 scenarios for Germany discounting optimisation values below 1

Feedstock	Alternative Fuel	Output	Distance (km)	Emission Reduction (%)	Cost (Euro/Toe)	Optimisation Value
Manure (biomethane)	Natural Gas	Injected	500	83	86	7.4
FRC	Coal	CHP	1-499	94	231	9.6
FRC	Coal	Heat	1-499	92	231	9.8
FRC	Natural Gas	CHP	1-499	91	231	10.0
FRC	Natural Gas	Heat	1-499	87	231	10.4
FRC	Coal	CHP	500-2499	92	231	13.5
FRC	Coal	Heat	500-2499	89	231	13.9
FRC	Natural Gas	CHP	500-2499	88	231	14.1

POLAND

Table 21 - Optimisation data; top 8 scenarios for Poland discounting optimisation values below 1

Feedstock	Alternative Fuel	Output	Distance (km)	Emission Reduction (%)	Cost (Euro/Toe)	Optimisation Value
FRC	Coal	CHP	1-499	95	165	3.4
FRC	Coal	Heat	1-499	93	165	3.4
FRC	Coal	CHP	500-2499	93	165	4.7
FRC	Coal	Heat	500-2499	90	165	4.8
FRC	Coal	CHP	2500-10000	88	165	8.5
Manure (biomethane)	Natural Gas	Injected	500	82	88	8.6
FRC	Coal	Heat	2500-10000	82	165	9.1
Straw	Coal	CHP	1-499	91	156	10.4

SPAIN

Table 22 - Optimisation data for Spain discounting optimisation values below 1

Feedstock	Alternative Fuel	Output	Distance (km)	Emission Reduction (%)	Cost (Euro/Toe)	Optimisation Value
Straw	Natural Gas	CHP	1-499	85	122	3.1
Manure (biomethane)	Natural Gas	Injected	500	83	100	3.1
Straw	Natural Gas	Heat	1-499	76	122	3.4
Straw	Natural Gas	CHP	500-9999	82	122	3.8
Straw	Natural Gas	Heat	500-9999	72	122	4.3
Straw	Natural Gas	CHP	10000+	75	122	5.7
Straw	Natural Gas	Heat	10000+	61	122	7.0

It is clear there is some overlap between scenarios appearing in each equivalent table reinforcing the desired propensity of the optimisation process towards the environmental component. The full result set, with consideration of AD processes outputting optimisation values below 1, will be considered in the discussion.

Figure 30 explores the influencing factors in determining the most successful scenarios and can be compared to Figure 17 to determine how this may change when the bio system is considered from a multi-criteria perspective. When cost is incorporated the results seem more reliant on the type of feedstock as this drives the economic component of the optimisation, whilst distance, output and alternative fuel remain of similar, but now comparatively smaller importance.

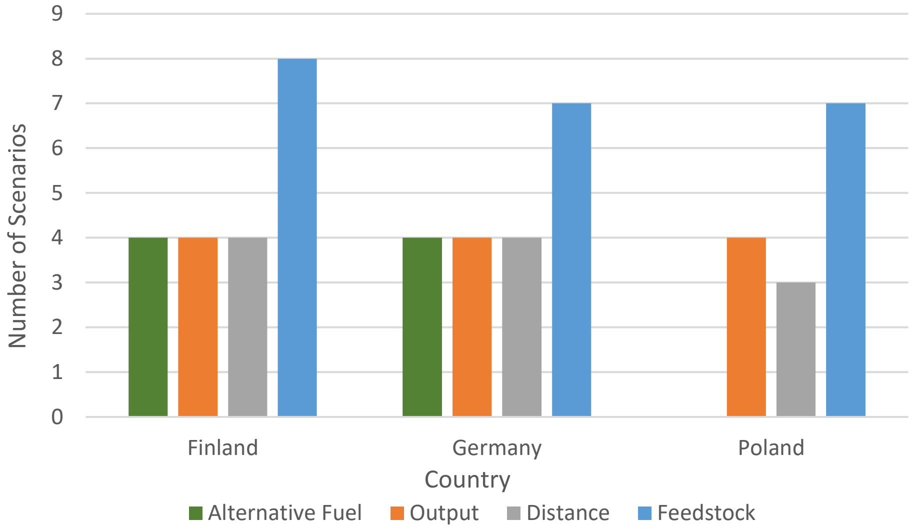


Figure 30 - Prevalence of influencing factors for best eight scenarios with a MCO using equation 2

The production of biogas from the anaerobic digestion of manure presents the optimum solution in Germany, Poland and Spain. With regard to combustion, both forest residue chips and straw have performed well in the optimisation process. The differences between the countries of use have been highlighted in Figures 31 and 32 for the case of a 0-499km transportation distance and CHP output.

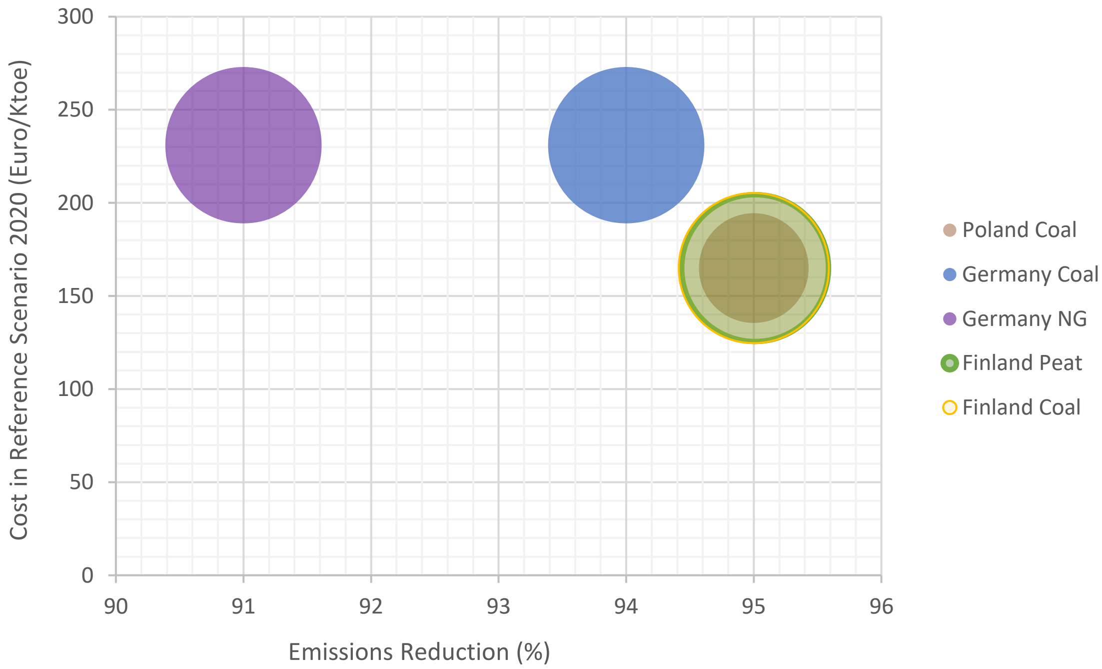


Figure 31 - Emissions, cost and potential of forest residue woodchip use in Poland, Germany and Finland

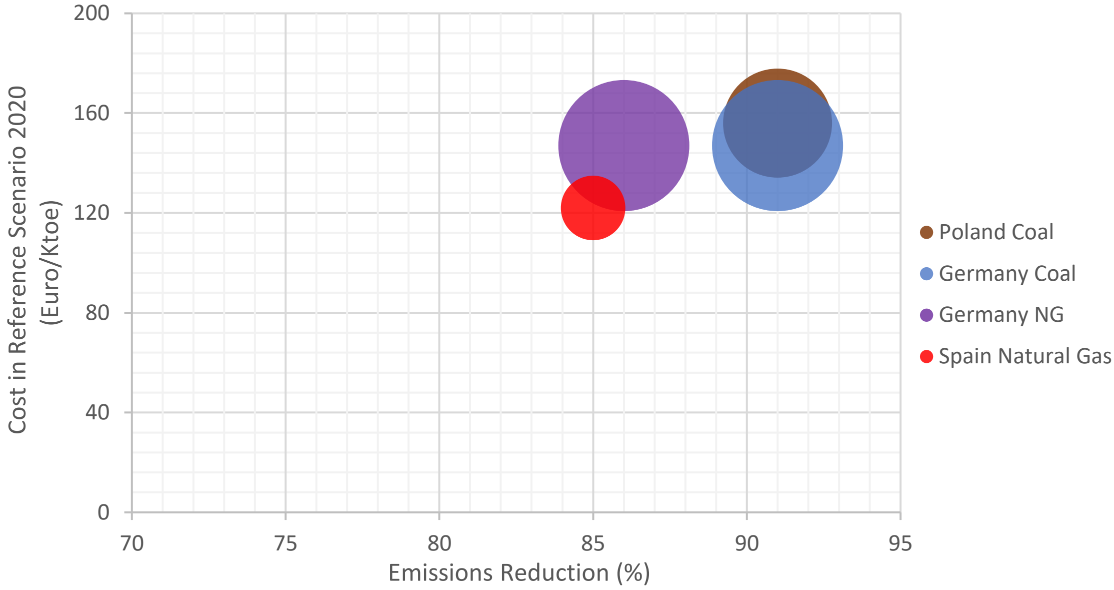


Figure 32 - Emissions, cost and potential of straw use in Poland, Germany and Spain`

The use of forest residues is shown to be most beneficial in Finland and Poland from an economic and environmental perspective, whereas the use of straw has greatest environmental benefit and the largest energy potential in Germany, but the best economic outlook in Spain. The environmental performance is worst when substituted for natural gas, however when forest residues were used as an alternative fuel source over peat and coal, they offered a 95% reduction in both cases.

To understand the spread in performance of all scenarios box and whisker plots were created to show the variation in both emission reduction and optimisation value. Figure 33a shows that emission reduction falls mostly between around 70-90% with little spread outside of the whisker points. Figure 33b shows that once optimised an increase in spread is visible however the majority of results sit in the lower range suggesting good performance from many scenarios.

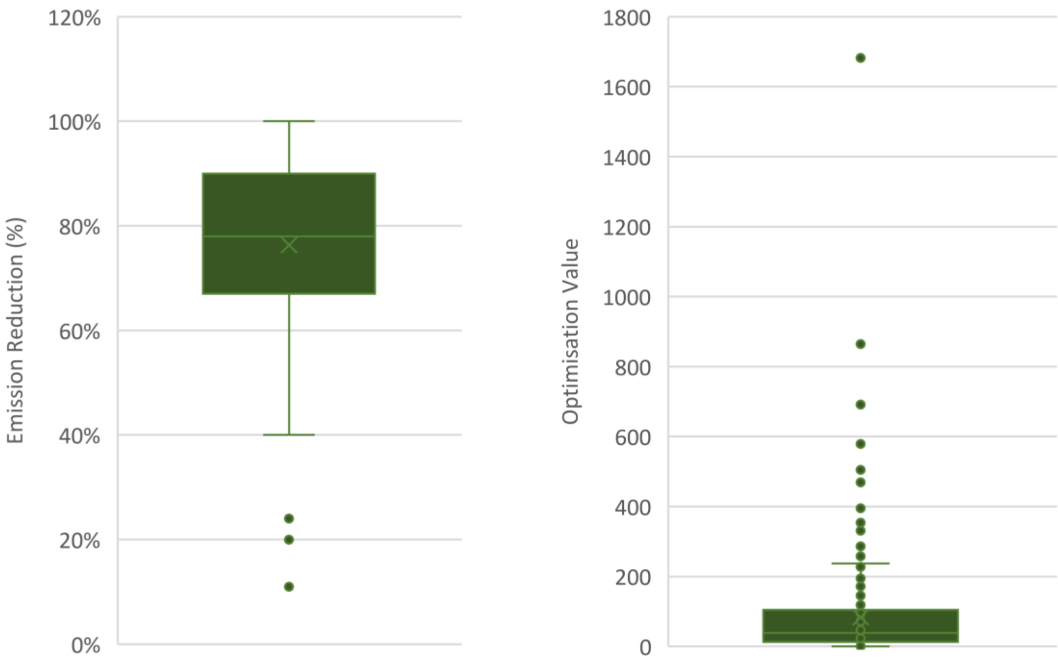


Figure 33 - Variation in a) emission reduction (left) and b) optimisation value (right) for all scenarios

5 Discussion

The results from the BioGrace tool can be reviewed based on their ranking in the multi-criteria optimisation process, but also by the emission reduction that can be achieved. All scenarios demonstrated the ability to achieve emissions reductions based on the likely alternative fuel, with a minimum reduction of 11%. This represents a positive response and highlights that any move to increased bioenergy penetration within DH systems, but also in heating systems in general, can achieve substantial environmental benefit. The scope for improvement was generally large with many scenarios offering emission reductions above 80% and optimisation values being generally low (Figures 33a and 33b). The best performing scenario was the anaerobic digestion of manure to create biogas for use in CHP systems, closely followed by the production of biomethane to be injected into the national grid. All scenarios producing biogas with transportation distances ranging from 5-500km created emission reductions over 100% and only biomethane production with a distance of 500km fell under a 100% emission. This suggests there is a maximum transportation distance, beyond which the manure based options are no longer the optimum solution. This distance will be slightly above 500km for biogas production and below 500km for biomethane production. The BioGrace tool was used to incrementally change transportation distance to acquire estimations of these values given in Table 23.

Table 23 - AD processes: transportation distance at which emission reduction reaches 100% and below that of the next best scenario

Country	Previous Best E_R (%)	Alternative Fuel Type	Biogas Distance (km)	Biogas E_R (%)	Biomethane Distance (km)	Biomethane E_R (%)
Spain	85%	Natural Gas	525	100	443	100
			590	84	**495**	84
Germany	95%	Natural Gas	525	100	443	100
			550	94	**462**	94
		Coal	525	100		
			560	94		
Poland	95%	Natural Gas	525	100	443	100
			546	94	**462**	94
		Coal	525	100		
			565	94		

Moving on from AD processes, a large amount of the analysis focused on the combustion opportunities surrounding each country and feedstock. The most successful combustion scenarios were largely based around straw use and forest residue woodchip use, with feedstock type proving to be a key variable (Figure 30). Straw use in CHP systems in Spain, substituting for natural gas was the optimum non-AD process. Any woody feedstock performed best in a scenario in which it was used in chip form, as opposed to pellet form. This is on account of the additional emissions and heat input required in the pellet production process. However, once in pellet form the feedstock is hydrophilic allowing easier storage and an ability to cope with seasonal demand. Crossover was found in the top eight scenarios when ranked by emission reduction or by optimisation value as seen by the green scenarios in Tables 19-21. This confirms that environmental impact was a key factor in the optimisation, as set out in the aims.

Straw use in Spain transported a distance of over 10,000km outperformed any Finland or Germany based scenario, which may suggest there is a benefit in pursuing this pathway, however Spain displayed a relatively low energy potential for Straw. When looking at scenarios based in Finland the top 12 scenarios involved the use of forest residue woodchips to a transportation distance up to

10,000km. At distances beyond this, it was advantageous to switch to stemwood chips transported distances up to 2500km, or forest residue pellets produced using a wood chip boiler and transported up to 10,000km before it would again be preferential to revert to forest woodchip use. This analysis is of particular importance when external factors affect the availability of either chipped or pellet based feedstock, such as unexpected production levels causing a reliance on the more readily storable pellet form of feedstock.

When considering the worst performing scenarios 19 out of the bottom 20 were implemented in Germany. This is due to Germany's current reliance on natural gas which has a lower emissions factor, and the low coal emission factor for Germany at 86.7 gCO_2eq/MJ, compared to that of Finland, Poland and Spain which range from 94.6-99.8 gCO_2eq/MJ (Table 2). This means that although net emission values may be the same, reduction potential in Germany is reduced. This does not mean that bioenergy should not be explored in Germany but it does highlight the potential benefit of transporting the woody residues to replace coal and peat use in Poland and Finland, and focusing efforts on manure and straw use in Germany and Spain. This pattern can be used throughout the EU, grouping countries by their emission potentials and current fuel use, and transporting feedstock types that optimally reduce overall emissions.

5.1 Distribution Considerations

Figures 16a-16c explored the effect of transportation distance on combustion scenarios in Poland. As transportation distance increased the emission reduction decreased and the variation between reductions for a heat only or CHP output increased. This was particularly evident for stemwood chips, forest residue chips and straw. When transporting feedstock shorter distances the output type has less effect on emission reduction potential and therefore it is these systems that should consider using a heat only output. Where longer transportation is required the benefit of using CHP systems is more pronounced and this should be of major consideration, for example CHP systems should be prioritised with imported biomass.

When scenarios are sorted by their optimised value, thereby considering economic impact alongside environmental impact, the importance of transportation distance was seen to decrease and feedstock type became more influential (compare Figures 17 and 30). Thus, the optimum solution may involve transporting the preferred feedstock type beyond its point of origin, in some cases for large distances. The exact payoff will depend on fuel mix and emission factors for the importing and exporting countries and the distances travelled. This research gives a broad view of expected trends however the same methodology can be used with more specific data, to explore the interdependencies of real situations in greater detail.

5.2 Availability Considerations

The bubble graphs given in 4.3.1 Visual Representation of Performance show the availability of each feedstock type through the size of bubble. Straw and manure are consistently seen to offer comparatively large availabilities at low cost and are therefore attractive options for increasing bioenergy use in DH. In Poland there is a visible difference in availability of type of woody feedstock; greater for stemwood compared to forest residues (see Figure 25 and Table 5). Finland has consistently high availability of wood based feedstock, however their market for manure is limited. The relationship between export and import levels demonstrates that Poland currently export relatively high proportions of their wood production compared to very low levels in Finland.

Following on from location-based availability are considerations surrounding seasonal availability. Figures 7-10 show the typical summer and winter load profiles in the selected countries. The key difference, unsurprisingly, is the larger demand on a typical winter's day for Finland, Germany and Poland, whereas for Spain the demand is generally larger on a typical summer's day. This can be explored further with a time-based study. The differences in gross level of demand, lowest in Finland and Poland, correlates to population size. Another research study for consideration could compare importing feedstock larger distances between climates with opposite demand profiles with storing the more GHG intensive pellet feedstock produced locally when demand was lower.

5.3 Potential Barriers and Risks

A key factor in applying the optimisation results to a real life scenario is the acknowledgment of external factors that will influence implementation. These have been highlighted in 4.1 Higher Level Analysis but have not been fully investigated. Poland was flagged in Table 8 as a country with high risk due to the current economic reliance on exported coal and a large coal share of DH. A substantial opportunity is presented for emission reduction but requires a change in attitude at a socio-political level. Poland has 3 scenarios in the overall top 8 however; arguably, when this high-risk label is considered more success could come from solutions in other countries. In contrast, Finland has a high RES share of DH and even though some DH is fuelled with coal and peat, the barriers to replacing these fuel sources have been identified as low risk. As a country Finland is on track to reach its NREAP targets which suggests a progressive attitude that would ease implementation and reduce risks.

5.4 Ethical Implications of Results

It is important to recognise that beyond the environmental and economic aspects accounted for within the optimisation process there are additional ethical implications. Forest and agricultural management is key in maintaining a sustainable bio-chain with positive social ramifications. The links between supply and demand mean that an increased demand for biomass is likely to drive increased prices that can threaten food security if not adequately managed. The effects surrounding potential land use or biodiversity change to supply bioenergy are far-reaching and this should be considered at national and EU policy levels. However, investment in biomass DH systems can create employment within an industry where demand is consistently increasing. Climate change is a significant current global issue and, assuming the political consensus continues, increasing pressure will be put on individual nations to cut carbon emissions. Creating new jobs and increasing the knowledge base will help to support this change as RES share targets increase and the need to take more urgent climate action is addressed.

5.5 Sensitivity to Optimisation Equation

Two optimisation equations were created to analyse the environmental and economic impact of each scenario. These were compared using base reference cases in Figures 28 and 29 and demonstrated that equation 1 showed the greater affinity to the economic component and equation 2 to the environmental component. Given objective 5 and the goal to optimise with primary regard to environmental performance it was thus decided to continue analysis using equation 2. This result was further highlighted when an individual scenario was traced, and achieved a ranking of 1st when optimised with regard to emission reduction only, which reduced to 99th for equation 2 and 169th with equation 1. However, there is argument for the use of equation 1 as there is a large spread of both series in Figure 28. This shows that neither equation offers an environmental component that closely resembles a sole environmental optimisation. Figure 29 represents the scenarios sorted only by feedstock cost and a more clear, closely following trend is seen here for equation 1. It is recognised that as both equations offered a large scatter in the environmental analysis it could be contended that the cost component should therefore be considered more highly. However, due to the nature of the research and its foundation in environmental impact and climate change mitigation, the use of equation 2 is justified.

The analysis has highlighted the sensitivity of the performance of each scenario to variations in the optimisation equation and has reinforced the idea that care must be taken to design an equation that accurately reflects the aim of the research. Were this research being conducted under different circumstance, for example in a political environment, equation 1 may be more useful.

5.6 Methodology Evaluation

The methodology was designed to be adaptable and although decisions were often made with the pressures of time constraints, the principles established can be carried through to expand the research. By conducting a two tier data collection process some verification and confidence in results is offered. The spread of BioGrace data (Figure 15), is seen to fit mostly within the values found in existing literature (Figure 13), and by using only one source the variations in system boundary and scope have been negated. Broadly, the analysis works well on a comparative basis when used against like-for-like data, however beyond this there may be restrictions in how the data can be used and limitations on the conclusions that can be drawn. The manure based emissions applied a sizeable credit associated with improved manure management that led the majority of these processes to outperform other scenarios. This is specific to the BioGrace tool and does not reflect the results found in wider literature searches as demonstrated in Figure 13. This presents a limitation to the current methodology and its ability to model AD of manure in line with existing literature.

The optimisation method offers two equations that can be used to optimise favouring either environmental or economic aspects. This means the method can be applied by multiple stakeholders and would allow each to analyse quantitatively a proposed solution and reach a compromise between each aspect of the optimisation. In addition the wide-ranging scoping section has provided a broader insight into additional factors that must be considered, and whilst not included in the optimisation process, they can be discussed alongside the results. Alternatively, the method could be expanded to account for these through the design and exploration of additional optimisation equations, which would address a current limitation of the method of optimising to only two criteria.

5.7 Limitations and Assumptions

The overarching aim of the research was to optimise bioenergy use within the EU. Due to the relatively short window of time, four countries of focus were chosen with the aim of applying the results in a broader landscape. This introduces a level of uncertainty when applying the results to an EU-wide discussion. To achieve the aim more accurately the study should be expanded and each member state analysed individually. Until that point countries must be grouped based on their similarities to the studied countries with regard to DH fuel mix, emission factors and feedstock potential. For example, those countries with wood and waste potential and high coal penetration may be grouped with Poland, a high natural gas penetration with Germany and a climate favouring grassy feedstock with Spain. Beyond this, only higher-level analysis can be applied on an EU basis. This includes general trends in performance of each feedstock or output type and the ability of scenarios with high transportation distances to outperform pathways with shorter distances when additional variables are more influential.

One limitation that became increasingly clear as work progressed was the justification behind many of the reviewed literature studies using fewer scenarios. The available data appeared to group itself naturally, for example by feedstock type or conversion technology and was the primary reason that analysis of Spanish systems was difficult. Spain was deliberately included to act as a comparator where the need for coolant systems may outweigh that of DH. Although the results seem different in this research they may not be anomalous if compared with other countries from a similar region. This tendency to create models or complete research around these natural groupings has meant that fitting a piece of work to bridge this gap in the literature has been difficult. The proposed methodology is limited to a narrow range of feedstock type making warmer climates, where grassy perennials present the cost effective and readily available solution, harder to analyse. To do this, the BioGrace tool would need to be expanded to allow the same methodology to be applied, and presents a major limitation to the progression of this research. An extension of this is the inaccuracy introduced through the use of the BioGrace tool. The BioGrace tool works with a number of assumptions including moisture content, transportation fuel and distance blocks. These make analysis possible within the shorter timeframe but also introduce some error. This was considered to have minimal affect when comparing scenarios but should be noted with regard to sitting in the wider body of research in the area.

6 CONCLUSIONS

The MCO equation considering both environmental impact and cost demonstrated that the optimal biomass pathway is anaerobic digestion of manure in Spain, Germany and Poland with scores of 0.26, 0.62 and 0.72 respectively (affected by the imposed constraints). This is due to the low feedstock cost and the GHG emission credit associated with improved manure management that is included in the BioGrace tool. Only three cases of manure performed worse than at least one form of biomass combustion, this being biomethane production substituting for natural gas with a transportation distance of 500km in Spain, Poland and Germany. This was investigated in more detail and the distances at which emission reduction no longer outperformed the next best option was found for the manure pathways in each country and is given in Table 23. In Finland the optimum solution was the use of forest residue chips for CHP systems when replacing peat or coal. Sensitivity of the objective function has been explored and demonstrated the potential to use multiple equations with each stakeholder putting forward an equation to best represent their interests. Scenario rankings can be compared and a compromise can be reached.

From the discussion it is clear that the optimisation of bioenergy is a complex problem, with multiple variables impacting the final result. One optimum solution may be valid in a particular location at a particular time but the overall picture will be more fluid. Seasonal changes in climate and demand will affect the available options and a more complete picture would be needed to model fully the EU situation. The proposed methodology can be recreated and expanded to add additional countries and feedstocks to achieve this. With more emphasis on countries with a higher summer demand, the potential of feedstock swaps between warmer and cooler climates could be investigated, offsetting the increased GHG from longer transportation against the reduced need for storable pellet feedstock, the production of which is carbon intensive. This research has identified patterns such as this that can be investigated in more detail with specific, accurate input values.

The final recommendations would be to encourage bioenergy use within DH through increased policy that sets ambitious climate targets. All scenarios offered some extent of emission reduction, with values ranging from 11% to over 100%, and therefore any move to achieve this is beneficial. Where the situation allows, anaerobic digestion of manure presents the optimum pathway assuming the distance is below that identified in Table 23, closely followed by the upgrading of the biogas to biomethane and injection into the grid. Combustion technologies should be used with a combined heat and power output and forest residues in chip form, for Finland, Germany and Poland. Where possible transportation should be minimised however, once cost was also considered this was seen to become a factor of reduced importance. This supports the recommendation of a healthy import/export relationship between EU member states that allows the appropriate feedstock type to be used where maximum environmental benefit can be achieved.

7 FUTURE WORK

This research had the overarching aim to optimise bioenergy use within DH systems in the EU, and concludes that in the countries studied, manure based pathways proved the optimum option, followed by combustion of forest residue chips for use in CHP systems. To expand this research further, three key areas for future work have been identified.

Firstly, the process can be replicated across the remaining member states of the EU to expand the database. Further analysis can then be conducted as to how this will affect the optimum use of resources. The ability to do this will be improved if member states better recorded district energy statistics and provided their own demand and supply mix breakdowns, which, for example, are not currently available for Spain.

Secondly, the methodology can be applied to investigate other heat systems beyond DH, and the potential use in other energy vectors, such as electricity. The BioGrace tool is able to model for cooling and electricity outputs, therefore the same approach and default values can be used. This will enable the creation of a large database with comparable material to create a holistic view of biomass use within the EU. The role of district cooling can be investigated as often systems can be married together utilising much of the same infrastructure. Similarities and differences between the various energy vectors can be identified and a more complex optimisation equation can be created to incorporate this into a wider industry optimisation.

Finally, the effect of tool selection can be investigated as many of the limitations identified stem from the selection of the BioGrace II tool. A major factor in the use of this tool is that it suits the short project timeframe. If more time were to be allocated to future research the GEMIS tool could be used and results could be compared. If a similar, logical methodology was applied it may help to address the limitations when comparing this data with wider literature. By comparing data gained through the BioGrace II tool and that obtained from a different tool, specific trends resulting from the tool used could be identified and any internal bias could be accounted for.

APPENDICES

APPENDIX I – CASE STUDIES

The following case study summaries were completed in the early stages of the research to aid background understanding of DH systems in Europe and to understand the technologies and feedstock used in exemplar cases.

COPENHAGEN, DENMARK

Denmark is a global leader in energy efficiency and has a long standing tradition in DH and CHP with energy policy supporting such technologies through tax exemptions and financial incentives. Within Copenhagen the DH market share reaches 98% with 2 multi-fuel and 1 biomass large scale system and 4 waste to energy CHP plants. The district heating capacity reaches around 3000MW and in 2014 biomass accounted for 30% of the fuel mix. In addition there are five district cooling plants with plans to develop more and integrate these into the current extensive DHC network to meet increasing cooling demands (42). The goal of becoming carbon-neutral by 2025 is driving the city to modify existing plants to a larger portion or complete switch to biomass fuels. Currently, most heat generation is through the combustion of municipal waste and combination fuels including coal, biomass, oil and gas. In Averdøre unit 2 uses a combination of natural gas, oil, straw and wood pellets and is one of the most energy efficient plants globally through the use of elevated steam data (59).

VILNIUS, LITHUANIA

Construction of the DH network in Vilnius began in the 1950’s and now reaches a DH share of 90% with a capacity of 2330MW. The production of DH is mostly reliant on natural gas powered CHP plants with the major heat plants also using some heavy fuel oil. By switching to domestic biomass use the country aims to produce major cost savings and reduce reliance on imported electricity and fuel. Lithuania aims to meet 70% of centralised heating demand using biomass with municipal waste expecting to account for a large portion of this. At a cost of 13.2 million USD a boiler in Vilnius CHP Plant-2 has been adapted to use a mixture of biomass and fossil resources. Plant-3 was shut down in late 2015, however there is some interest in plans to convert the plant to biomass operation to further reduce heat costs by up to 22%. There is potential for this to be funded through EU channels (60).

STOCKHOLM, SWEDEN

Sweden has ambitions to become carbon neutral by 2045 and recognises district energy systems as a key feature of achieving this and offers financial support for transitions to such systems. The main DHC operator, Fortum Värme accounts for around 80% of the heat market share in Stockholm. It is a public-private partnership with 7 CHP plants and a total heating capacity of around 3600MW. Additional technologies are used including heat pumps and electric boilers. The DH fuel mix has moved from 100% fossil fuel in the 1970’s to largely renewable with biomass and waste holding the greatest market share. With this there has been a significant reduction in the CO_2 emissions related to DH (42).

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